

SPHEREx

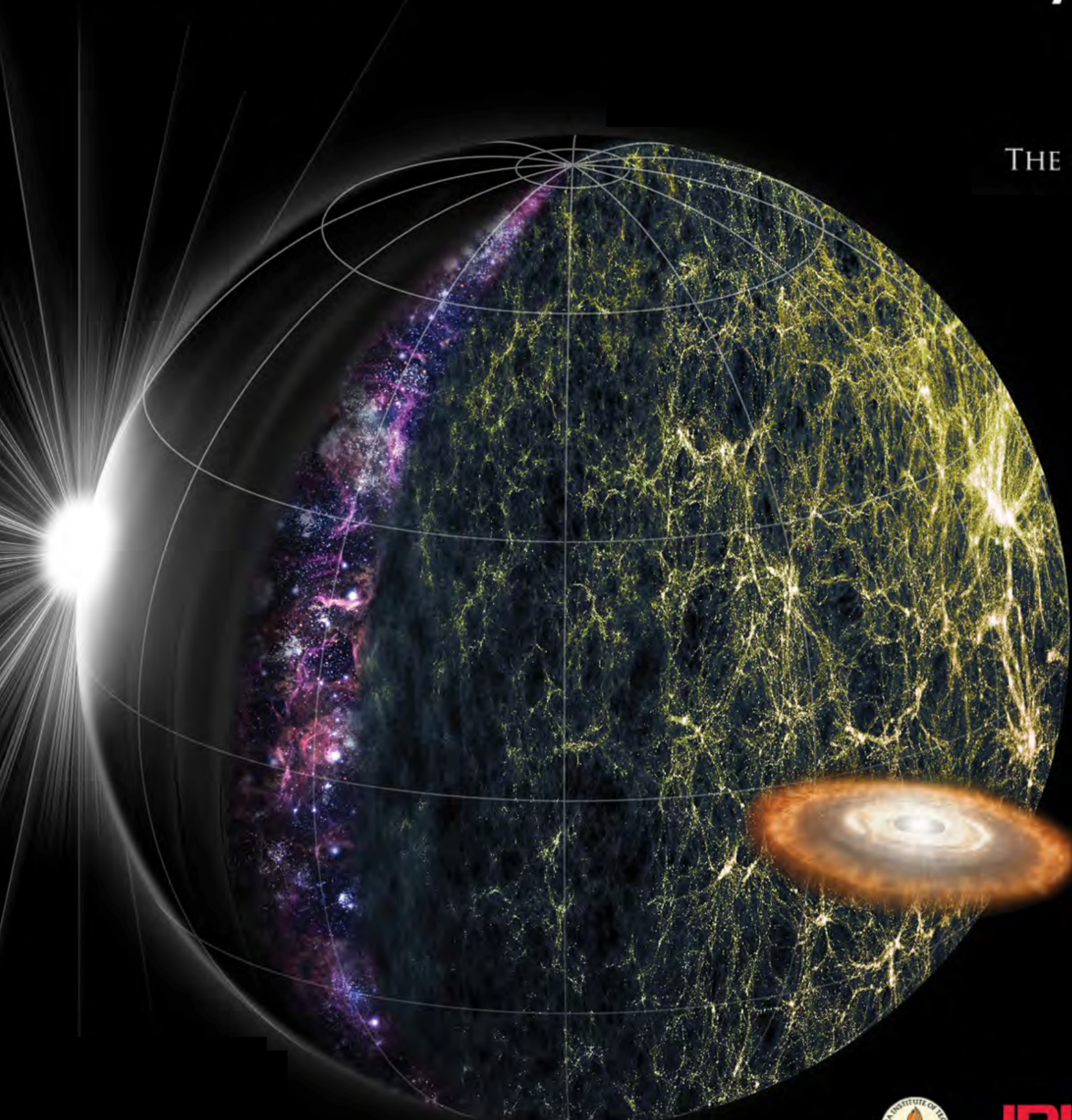
An All-Sky Spectral Survey

DESIGNED TO EXPLORE:
THE ORIGIN OF THE UNIVERSE
THE ORIGIN AND HISTORY OF GALAXIES
THE ORIGIN OF WATER IN PLANETARY SYSTEMS

Olivier Doré
JPL/Caltech

for the SPHEREx team

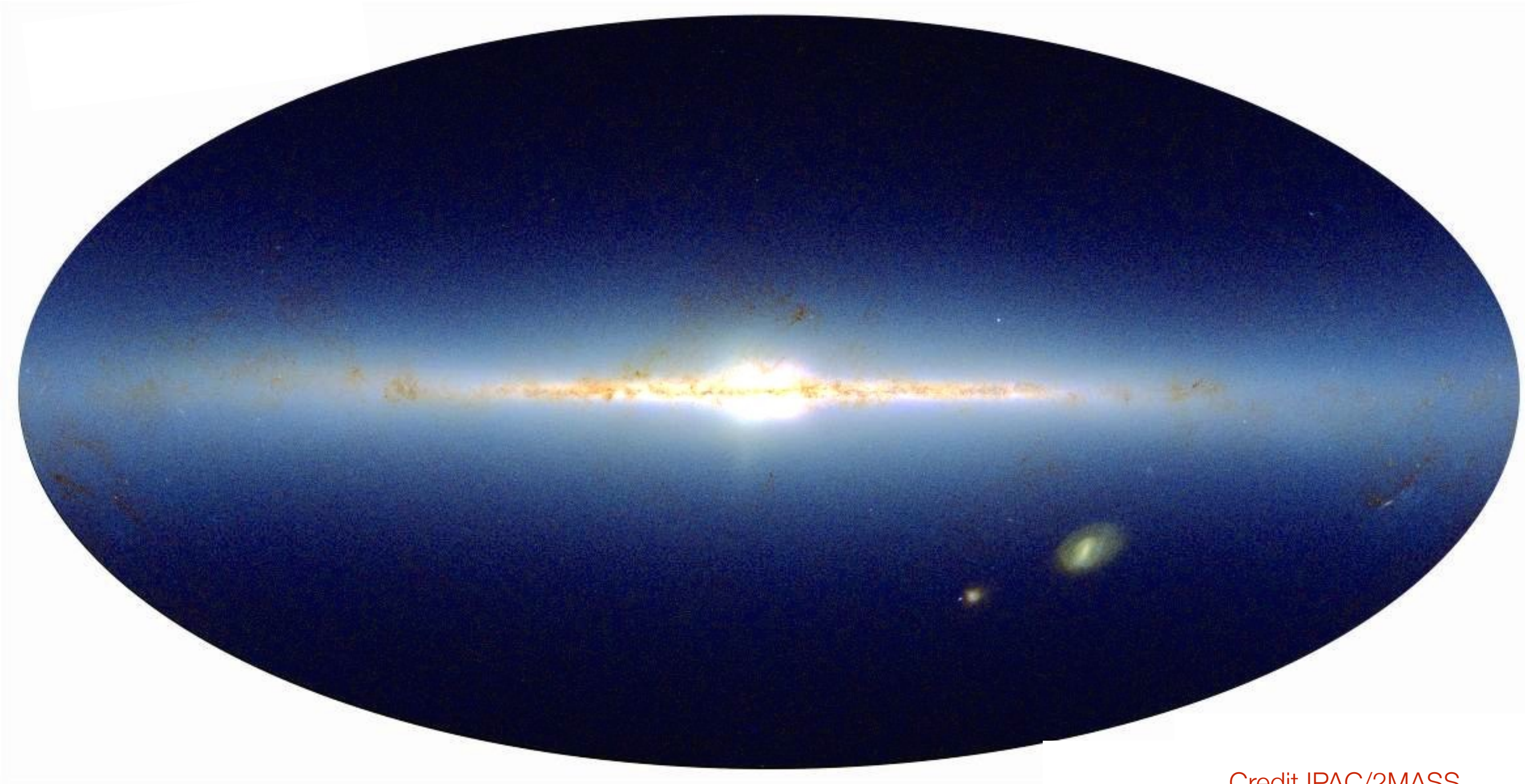
<http://spherex.caltech.edu>



SPHEREx: An All-Sky Spectral Survey

Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer

A high throughput, low-resolution near-infrared spectrometer.

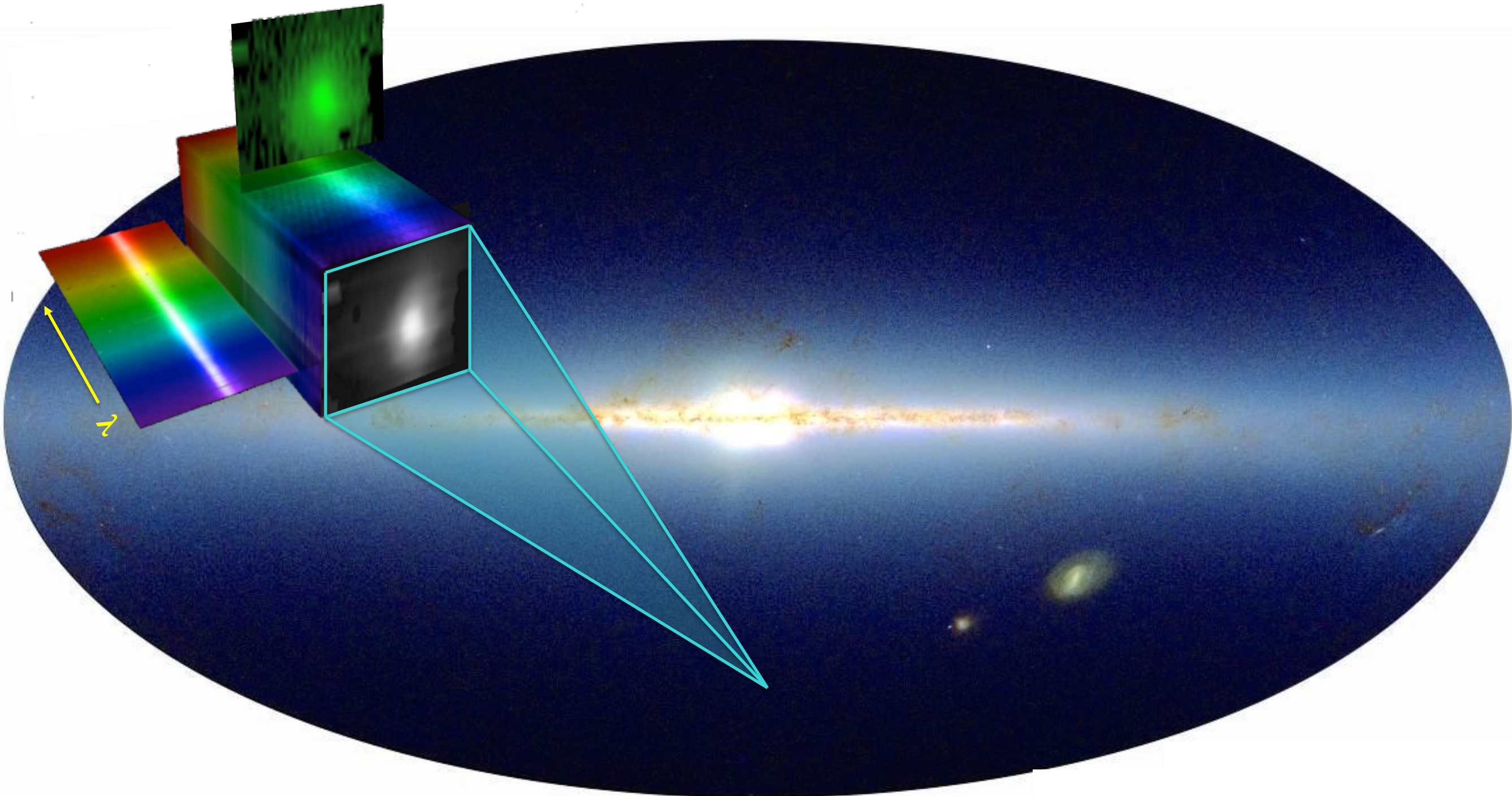


Credit IPAC/2MASS

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SPHEREx Dataset:

For every 6.2" pixel over the entire sky:

- R=41 spectra spanning ($0.75 \mu\text{m} < \lambda < 5.00 \mu\text{m}$).
- R=135 spectra ($4.18 \mu\text{m} < \lambda < 5.00 \mu\text{m}$).

O.D., Bock et al., arXiv:1412.4872

Three Major Scientific Themes

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- Inflation Investigation:
 - ➔ Cosmology with the 3D clustering of galaxies.
 - ▶ Survey the $z < 1.5$ Universe to fundamental limits to measure signatures of inflation (non-Gaussianity, primordial power spectrum shape) and dark energy.
 - ▶ Complement Euclid & WFIRST which survey smaller area at $z > 1$.

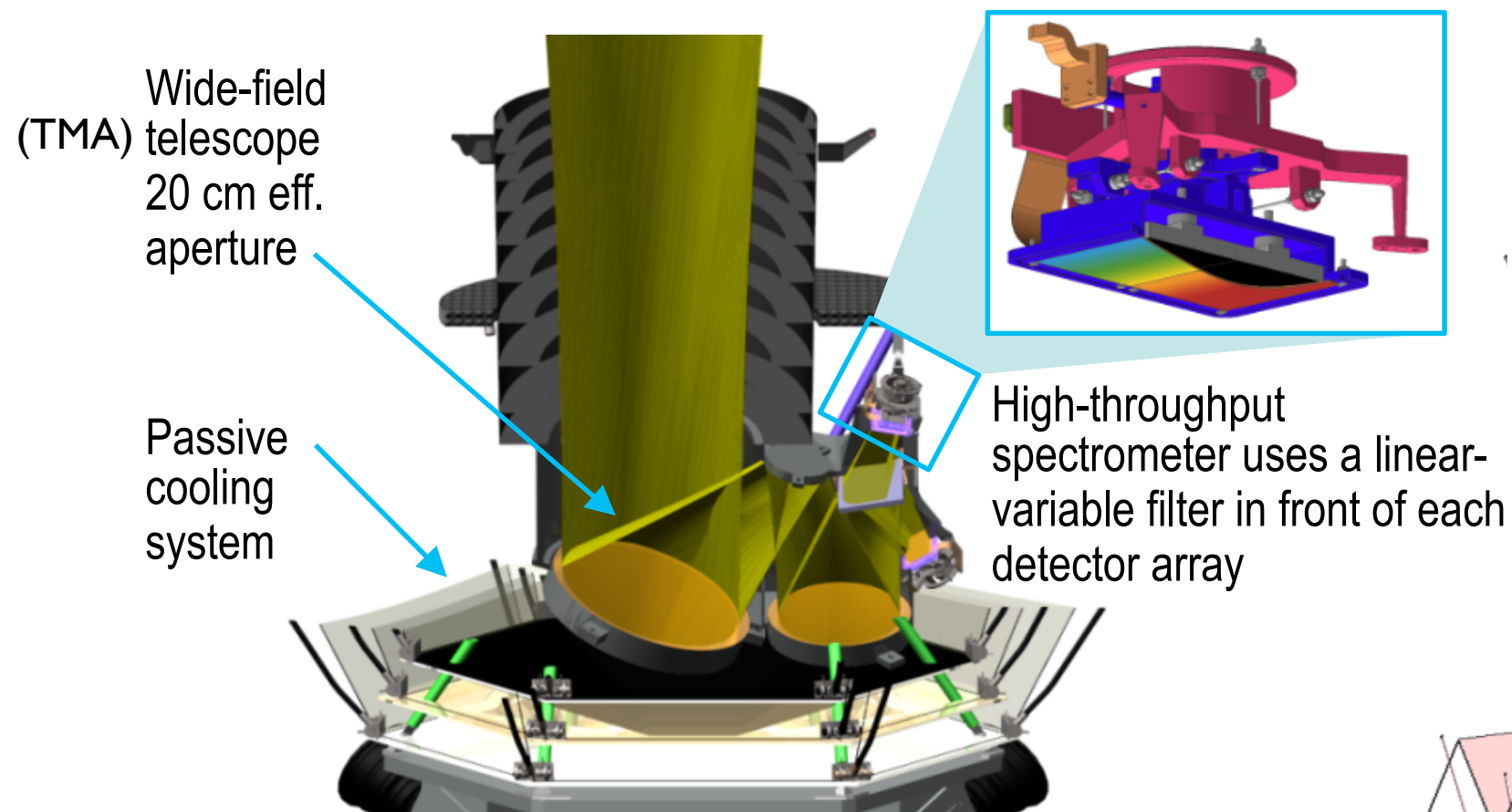
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- Galaxy Evolution Investigation:
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- Ice Investigation:
 - ➔ Measure broad absorption features in stellar spectra to explain how interstellar ices bring water and organic molecules into proto-planetary systems.

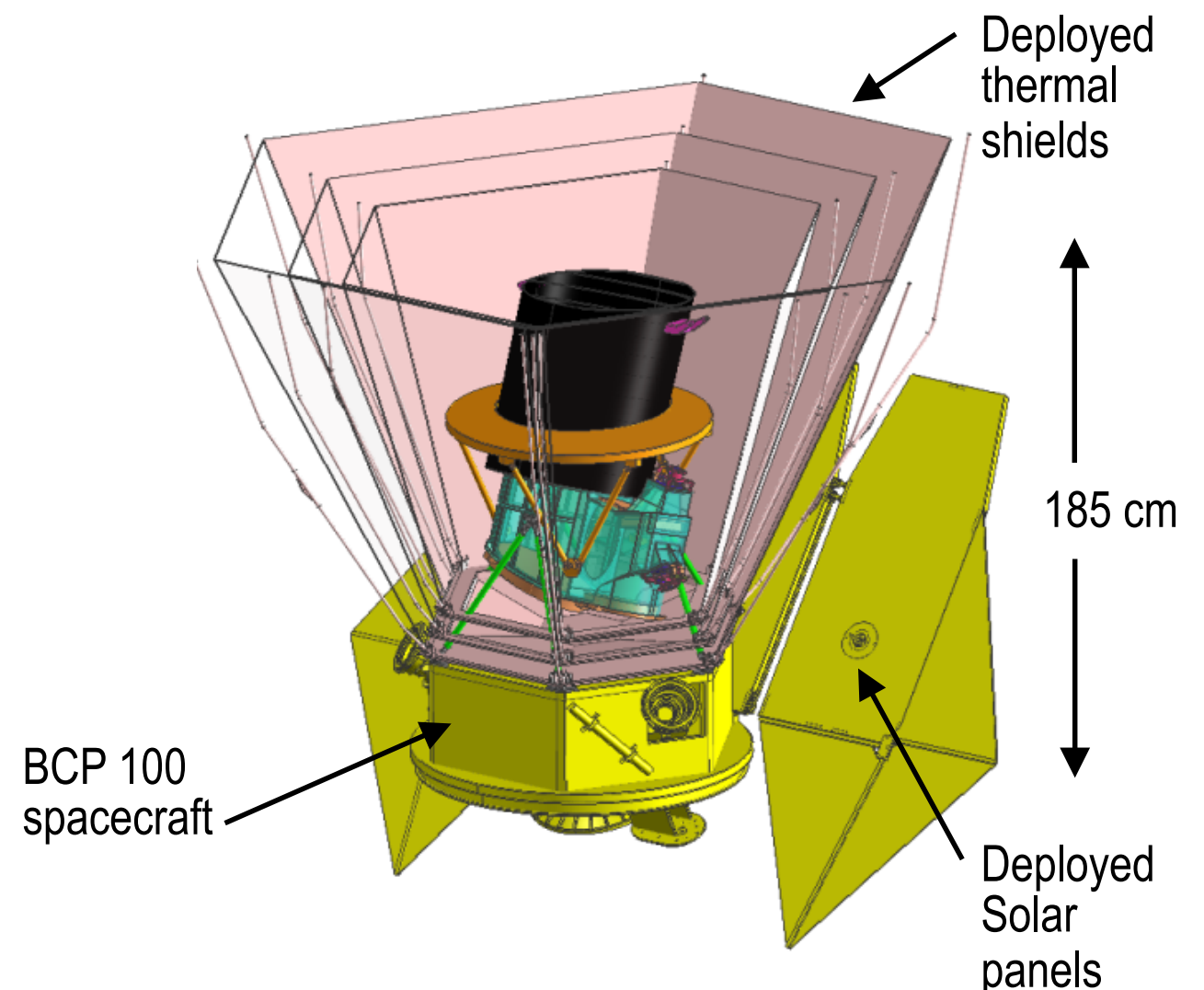
A Simple Instrument with Large Margins



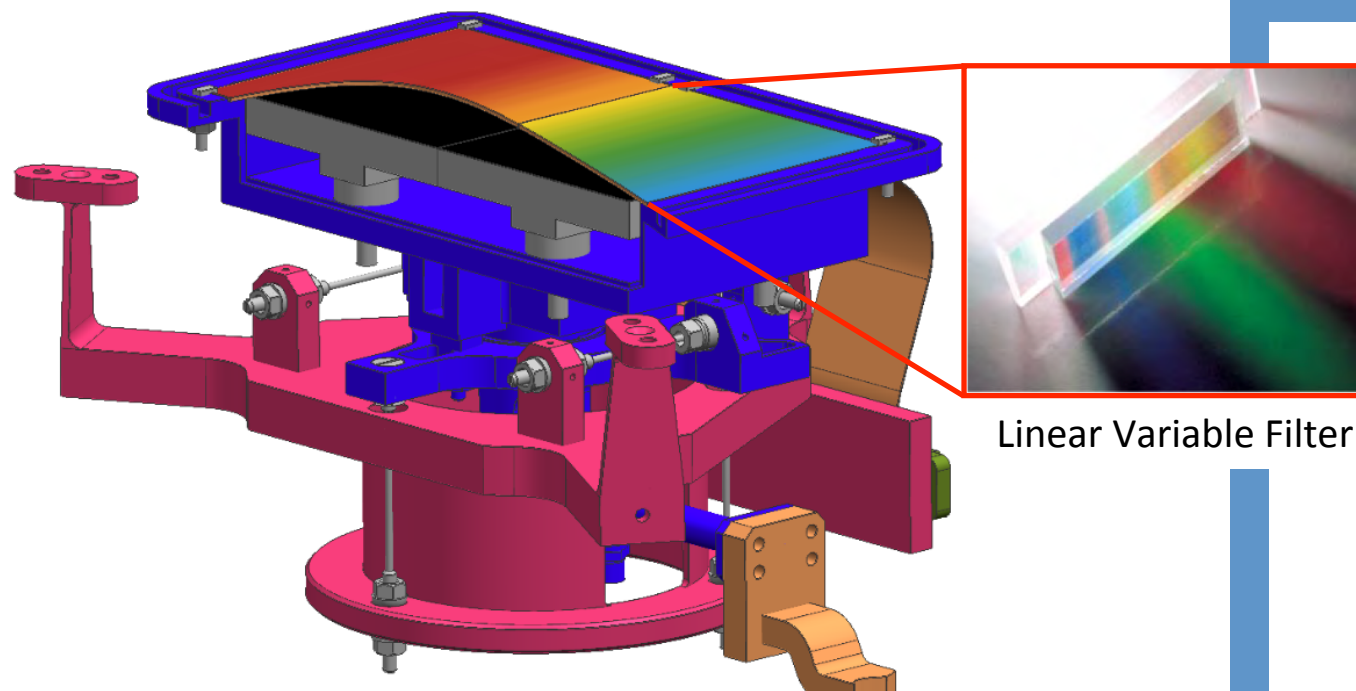
SPHEREx has uniquely large spectral light-collecting power for mapping the entire sky

Instrument & Mission Parameters

Parameter	Value	Parameter	Performance	Margin
Telescope Effective Aperture	20 cm	Spacecraft	Ball BCP 100	N/A
Pixel Size	6.2" x 6.2"	Science Data	73 Gb/day	97%
Field of View	2 x (3.5° x 7.0°); dichroic	Downlink		
Spectrometer	Linear-Variable Filters	Pointing Stability	2.1" (1 σ) over 200 s	43%
Resolving Power and Wavelength Coverage	R=41.5 λ =0.75 - 4.1 μ m R=150 λ =4.1 - 4.8 μ m	Pointing Control	22.7" (1 σ)	164%
Arrays	2 x Hawaii-2RG 2.5 μ m 2 x Hawaii-2RG 5.3 μ m	Pointing Agility	70° in 116 s (large slews) 8.8' in 6 s (small steps)	29% 233%
Point Source Sensitivity (MEV Performance)	18.5 AB mag (5 σ) with 300% margin to req't	Observatory Mass	173.6 kg (MEV)	53%
Cooling	All-Passive	Observatory Power	171.8 W (MEV)	36%
2.5 μ m Array and Optics Temperature	80 K with 700% margin on total heat load	Solar Array Power Output (EOL)	234 W	N/A
5.3 μ m Array Temperature	55 K with 450% margin on total heat load			
Payload Mass	68.1 kg (CBE+31% Ctg)			
Payload Power	27.8 W (CBE+30% Ctg)			

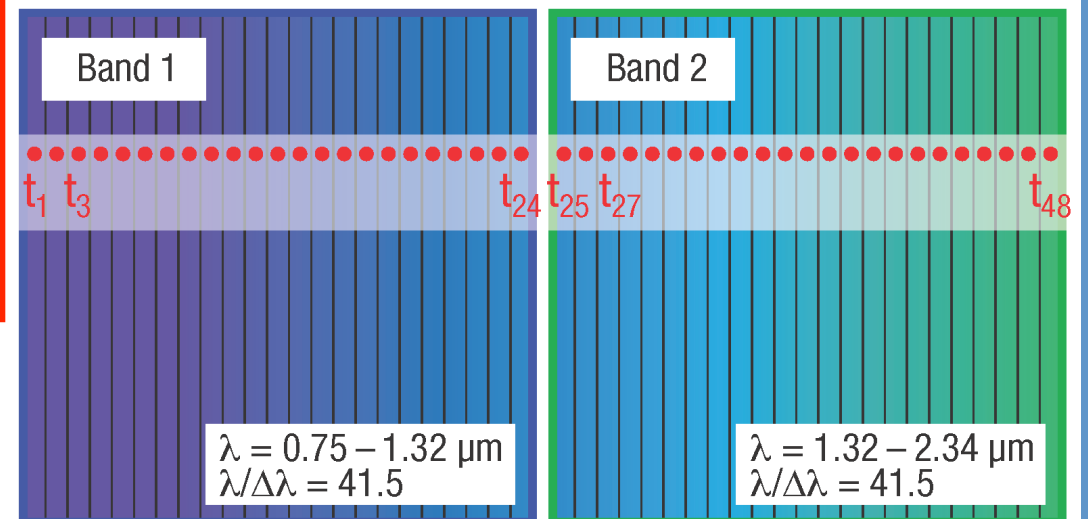


High-Throughput LVF Spectrometer

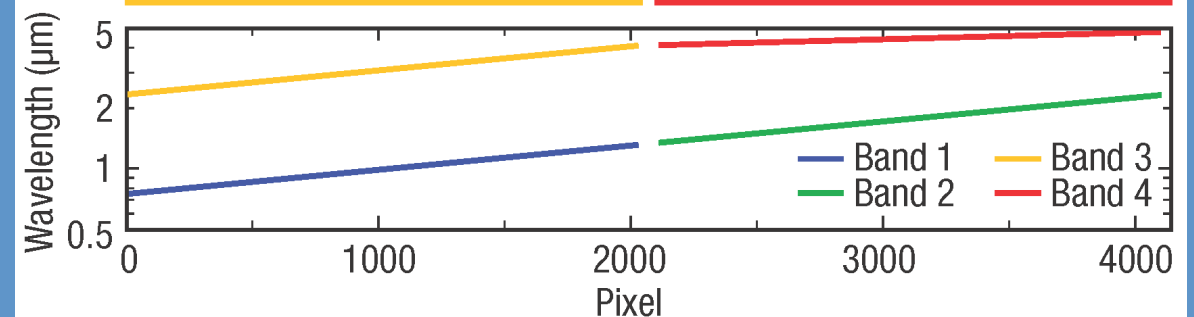
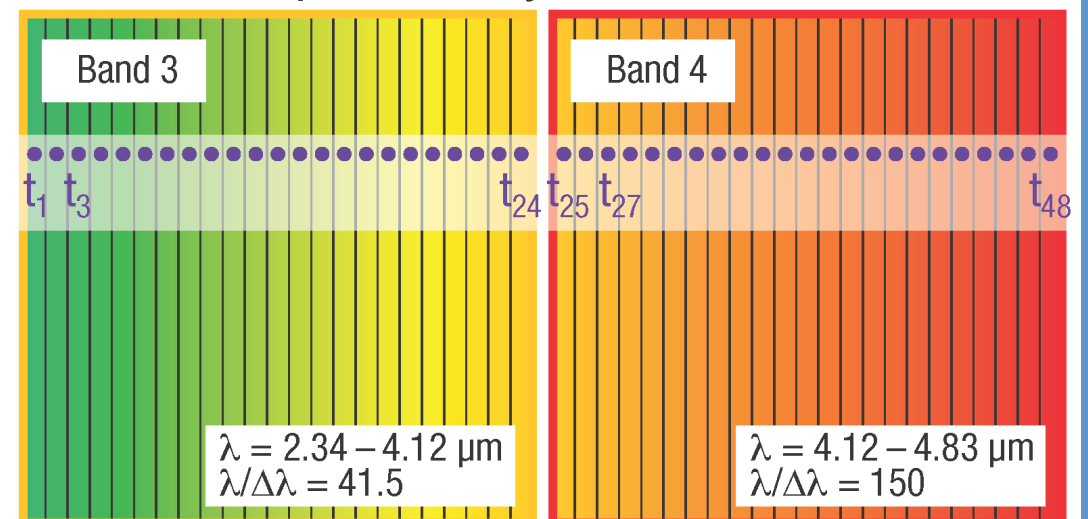


Linear Variable Filter

2.5 μm H2RG Arrays in Reflection

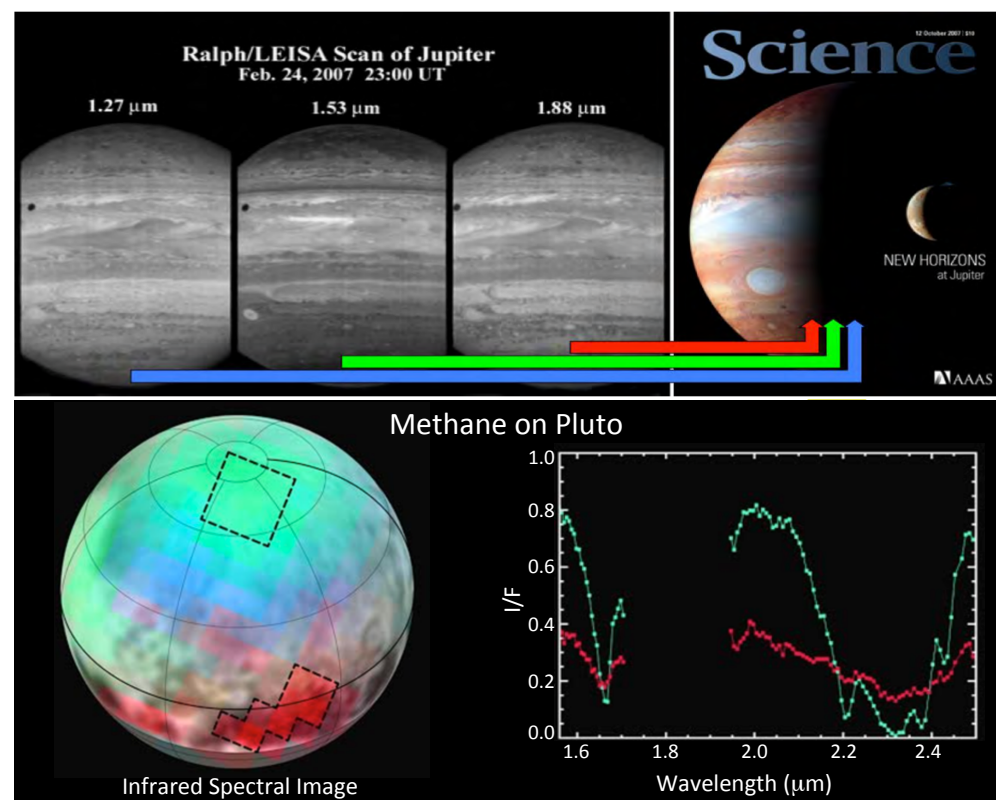
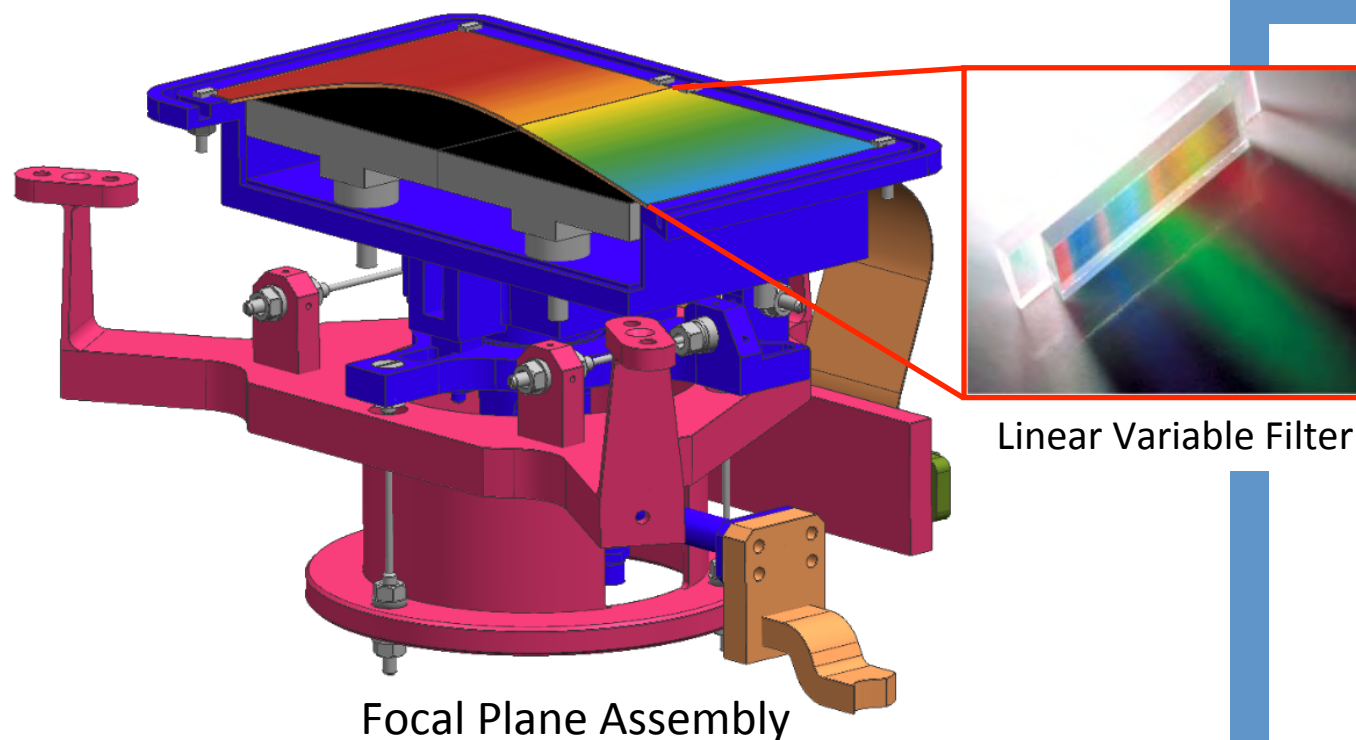


5 μm H2RG Arrays in Transmission

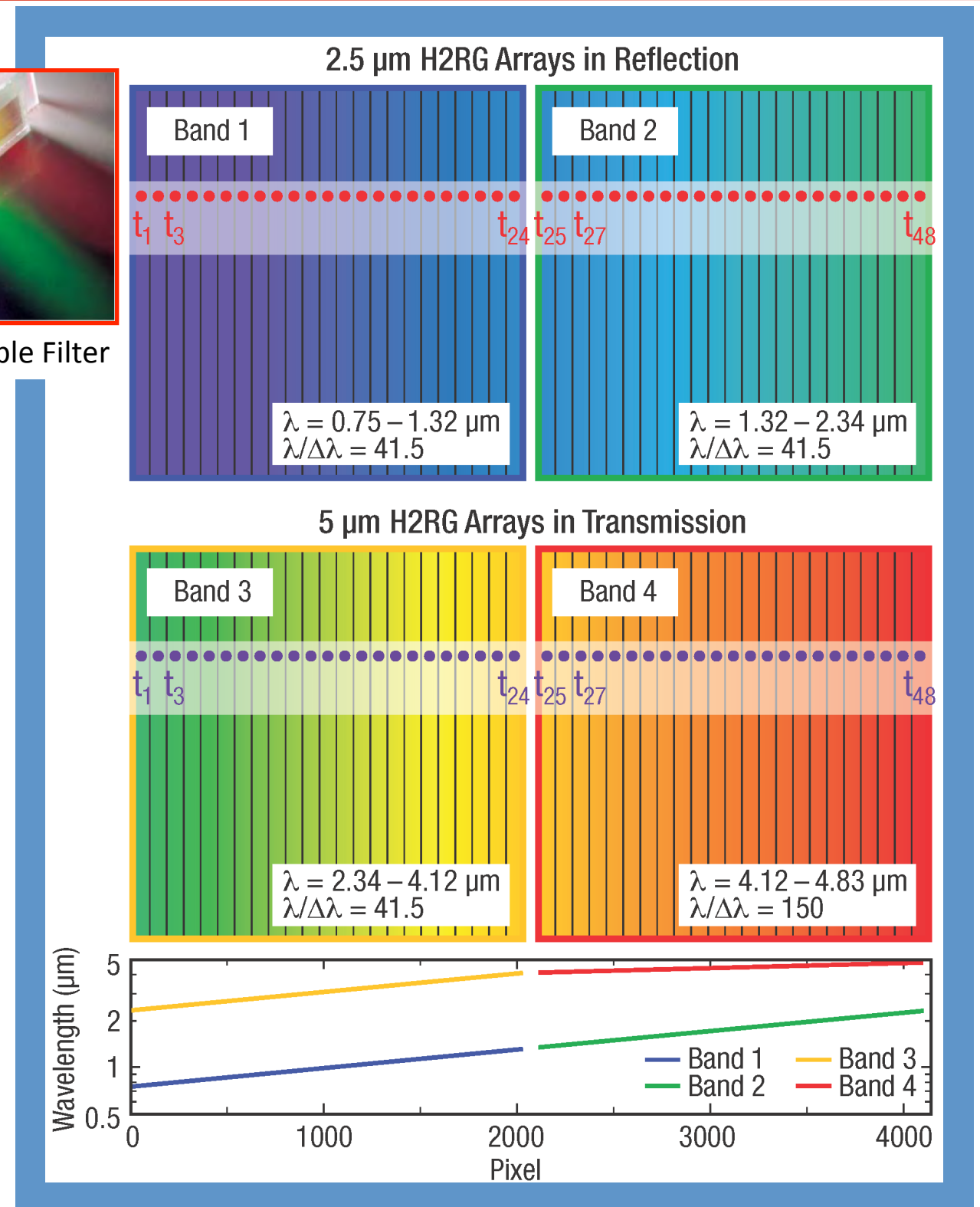


Spectra obtained by stepping source over the FOV in multiple images: **no moving parts**

High-Throughput LVF Spectrometer



LVFs used on ISOCAM, HST-WFPC2,
New Horizons LEISA, & OSIRIS-Rex (2016 launch)

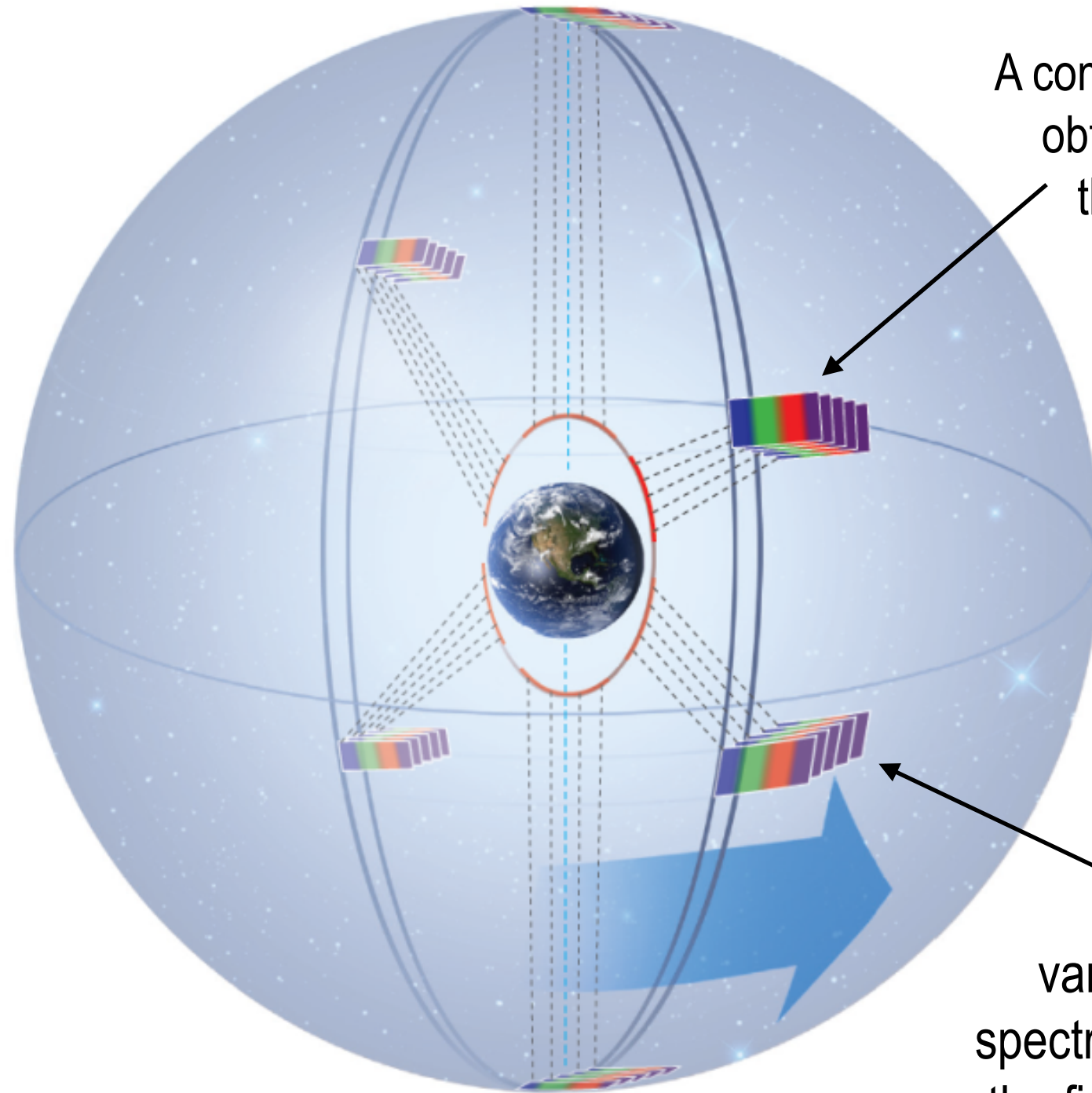


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An Efficient All-Sky Survey in a Step and Repeat Fashion

SPHEREx maps the entire sky with one simple observing mode:

- ➡ The spacecraft steps and points the wide-field telescope, tiling the sky every 6 months.
- ➡ Multiple images produce complete spectra over the full sky.
- ➡ The sun-synchronous LEO orbits enable simple passive cooling for NIR detectors.
- ➡ Naturally build regions near the ecliptic poles which are ~30x deeper.



A complete spectrum is obtained by stepping the field of view with the spacecraft and stacking images

SPHEREx images through linear variable filters, so the spectral response varies over the field of view

Very efficient survey: 85% of the time is dedicated to science

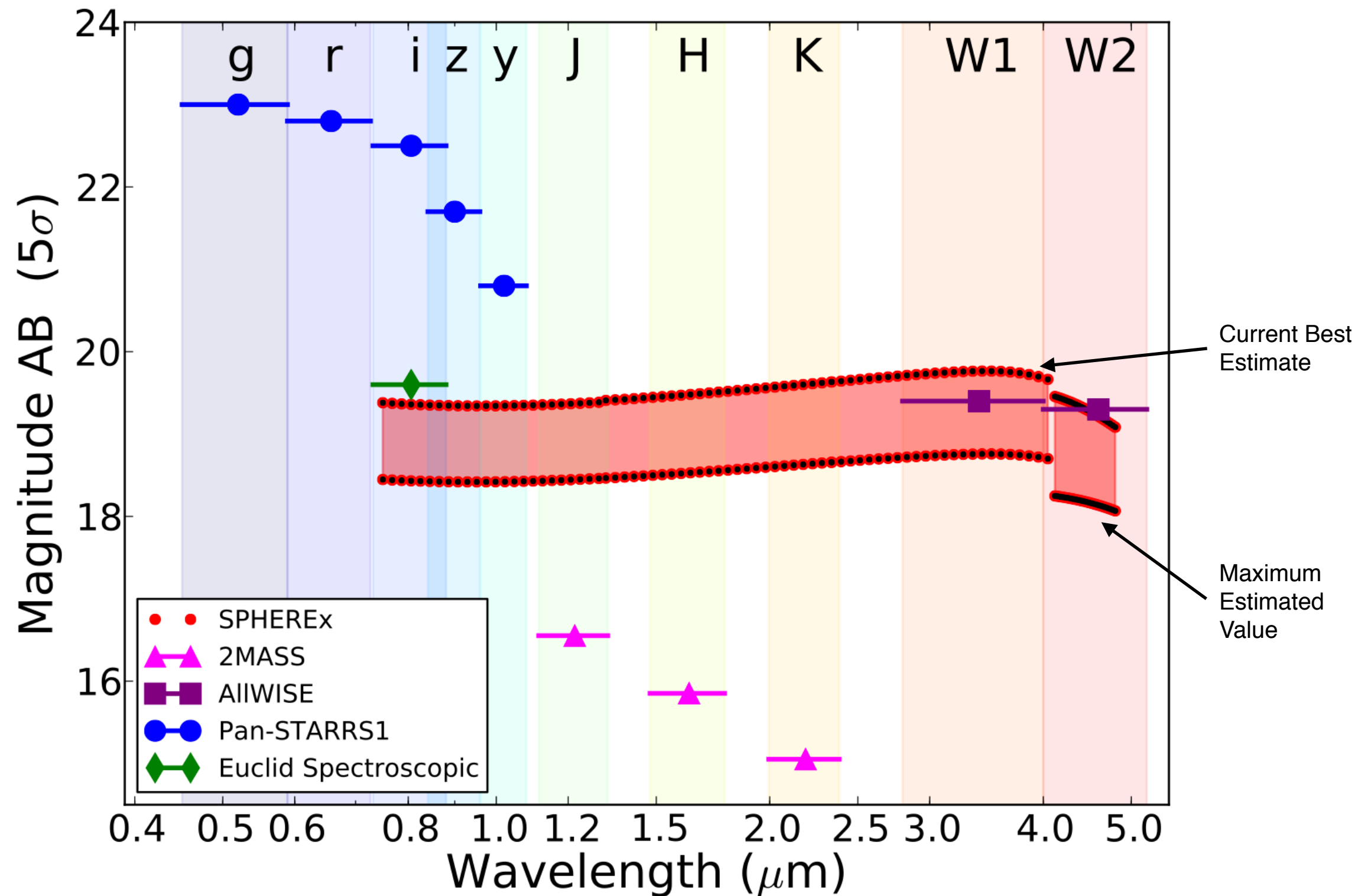
Spangelo et al., arXiv:1412.3142

SPHEREx Team



Jamie Bock (PI)	Caltech/JPL	Roland de Putter	JPL
Matt Ashby	CfA	Tim Eifler	JPL
Peter Capak	IPAC	Nicolas Flagey	IfA
Asantha Cooray	UC Irvine	Yan Gong	UC Irvine
Olivier Doré (PS)	JPL/Caltech	Elisabeth Krause	Stanford
Chris Hirata	OSU	Daniel Masters	Caltech
Woong-Seob Jeong	KASI	Phil Mauskopf	ASU
Phil Korngut	Caltech	Bertrand Menneson	JPL
Dae-Hee Lee	KASI	Hien Nguyen	JPL
Gary Melnick	CfA	Karin Öberg	CfA
Roger Smith	Caltech	Anthony Pullen	CMU
Yong-Seon Song	KASI	Alvise Raccanelli	JHU
Stephen Unwin	JPL	Volker Tolls	CfA
Michael Werner	JPL	Salman Habib	Argonne
Michael Zemcov	RIT	Katrin Heitmann	Argonne
		Marco Viero	Stanford
		Chang Feng	Irvine

SPHEREx All-Sky Survey Depth



A Very Rich Galaxy Catalog

Detected galaxies	1.4 billion	Properties of distant and heavily obscured galaxies
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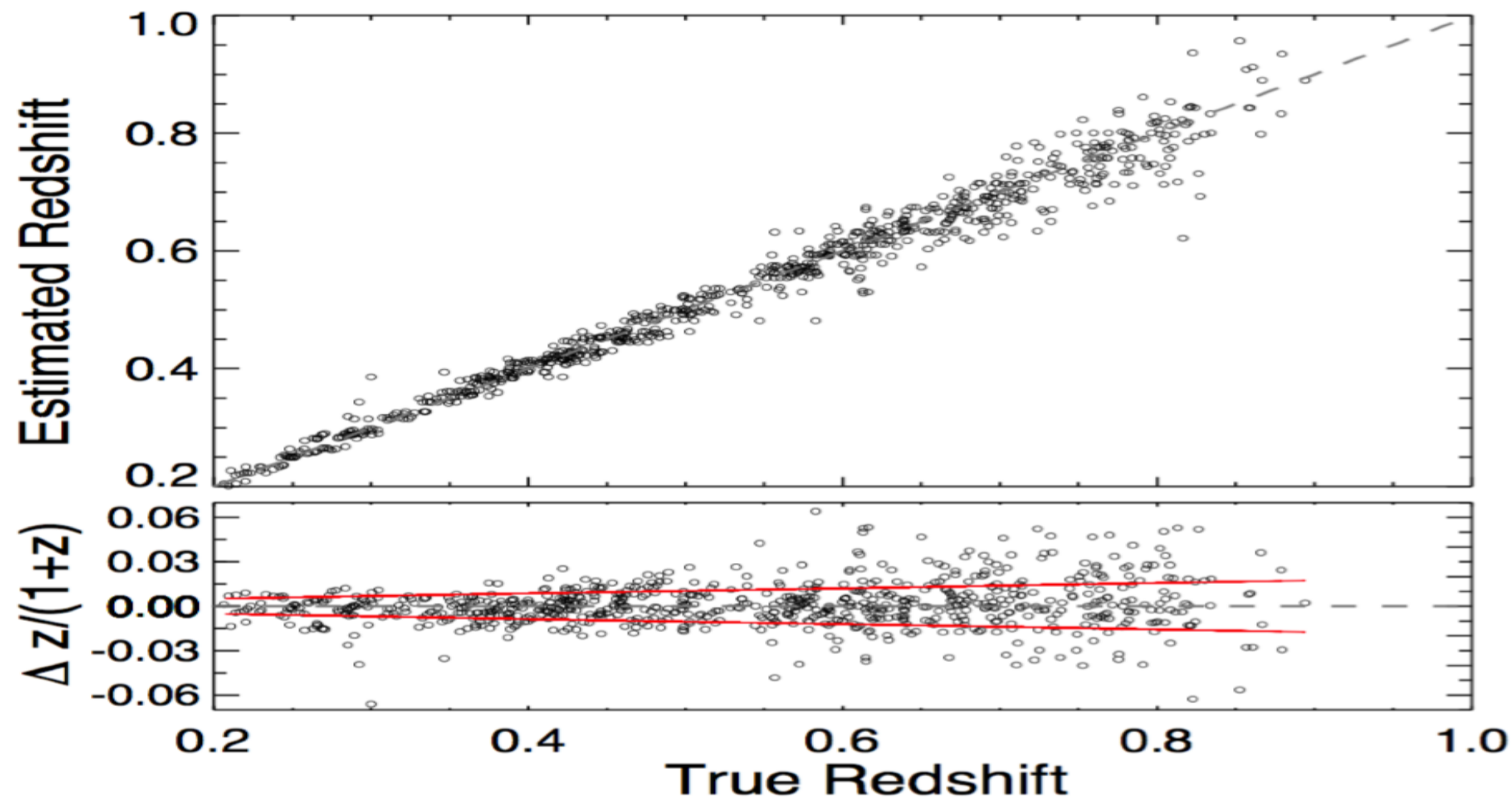
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Clusters with ≥ 5 members	25,000	Redshifts for all eRosita clusters. Viral masses and merger dynamics

And Much More...

Main sequence stars	> 100 million	Test uniformity of stellar mass function within our Galaxy as input to extragalactic studies
Mass-losing, dust forming stars	Over 10,000 of all types	Spectra of M supergiants, OH/IR stars, Carbon stars. Stellar atmospheres, dust return rates, and composition of dust
Brown dwarfs	>400, incl. >40 of types T and Y	Atmospheric structure and composition; search for hazes. Informs studies of giant exoplanets
Stars with hot dust	>1000	Discover rare dust clouds produced by cataclysmic events like the collision which produced the Earth's moon
Diffuse ISM	Map of the Galactic plane	Study diffuse emission from interstellar clouds and nebulae; hydro-carbon emission in the $3\mu\text{m}$ region

- A community workshop was held in Pasadena in February 2016 to discuss other science studies:
 - ➔ Very broad range of applications: comet and asteroid science, target finding for JWST (high z QSOs, unusual stars, ...), full sky line mapping (PAH, Paschen- α , Brackett- α mapping), etc....
 - ➔ A detailed 85 pages long report to appear next week (Ashby et al. 2016)

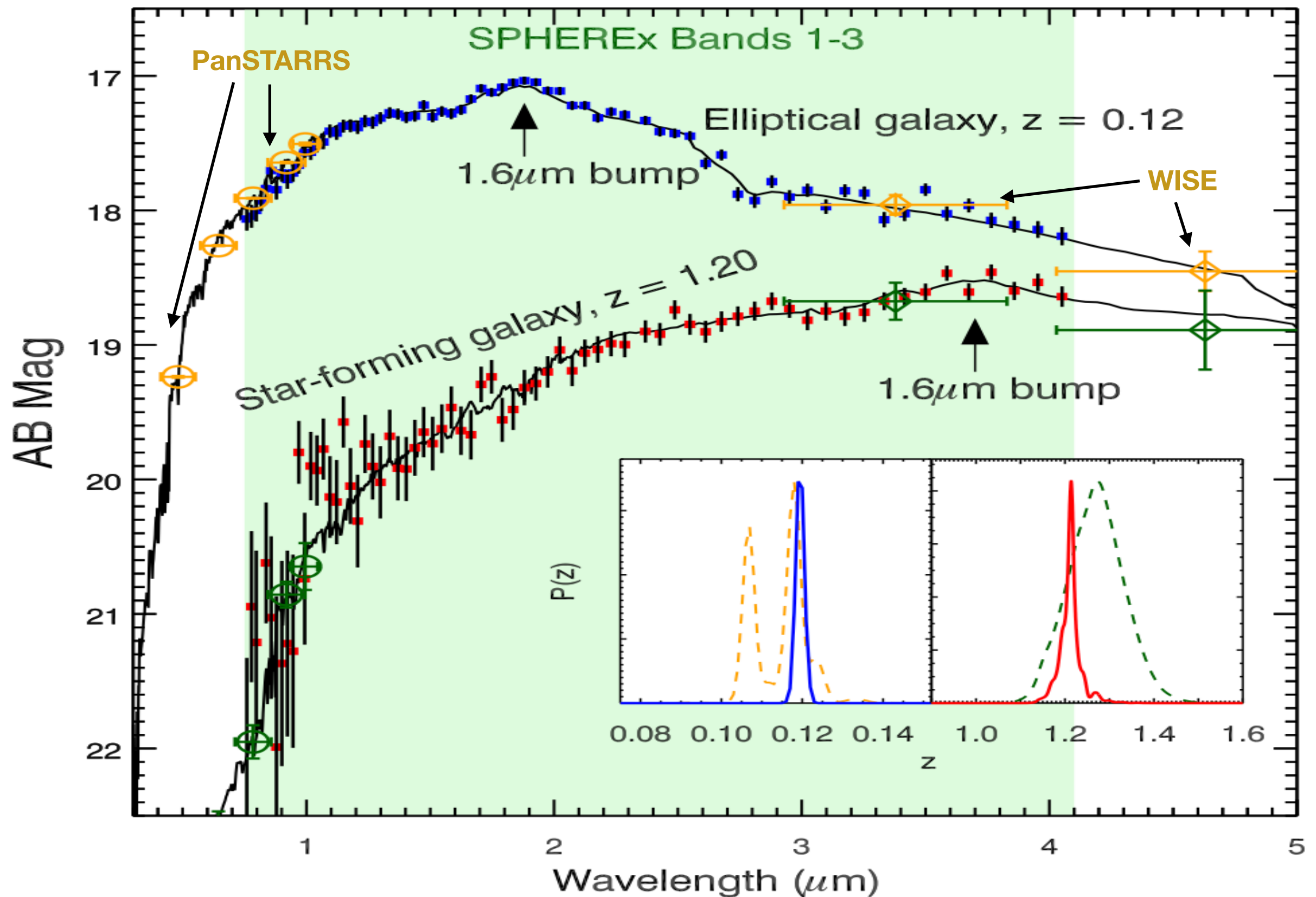
Galaxy Cluster Redshift Estimation



Lindsey Bleem

- Simulation of 800 clusters identified with DES redMaPPer algorithm ($M_{500c} < 10^{14} M_{\text{sun}}$)
 - ➔ Using only SPHEREx spectra of galaxies identified in DES.
 - ➔ Precision using SPHEREx alone exceed that of optical surveys at $z < 0.6$ and remains excellent ($\sigma(z)/(1+z) < 0.03$) at $z \sim 0.9$.
 - ➔ Will do even better in combination with DES or LSST.
 - ➔ Particularly valuable in conjunction with A-ACT, SPT-3G, S4, Simons Array, eROSITA.
- Also stacking of LSST sources in SPHEREx is very promising (Padmanabhan, White, ... 16)

Building a 3-D Galaxy Catalog with SPHEREx



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 - ➔ [For each galaxy, redshift but also other properties \(stellar mass, dust content...\).](#)
 - ➔ [The 1.6 \$\mu\text{m}\$ bump is a well known universal photometric redshift indicator \(e.g., Simpson & Eisenhardt 99\).](#)

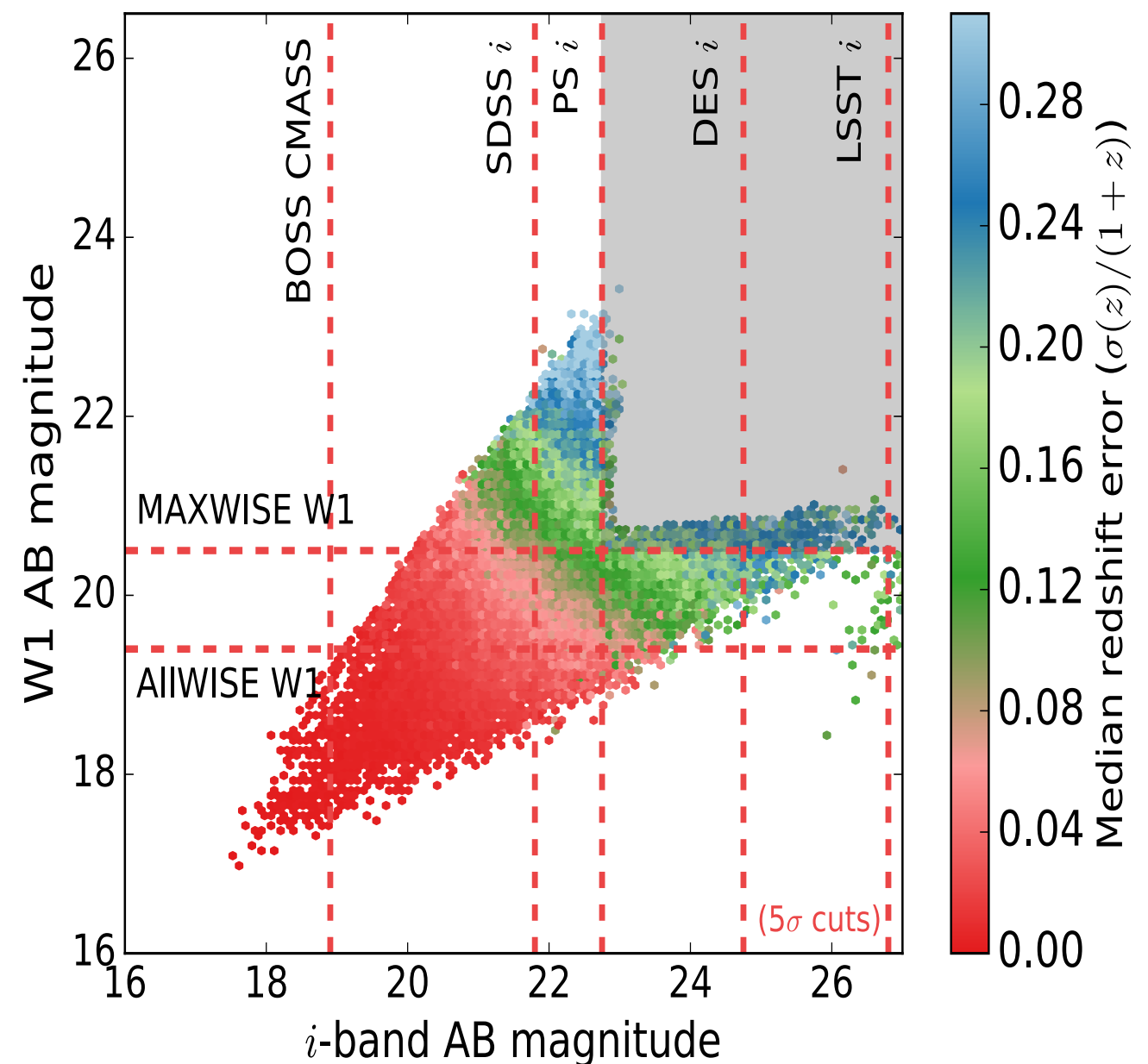
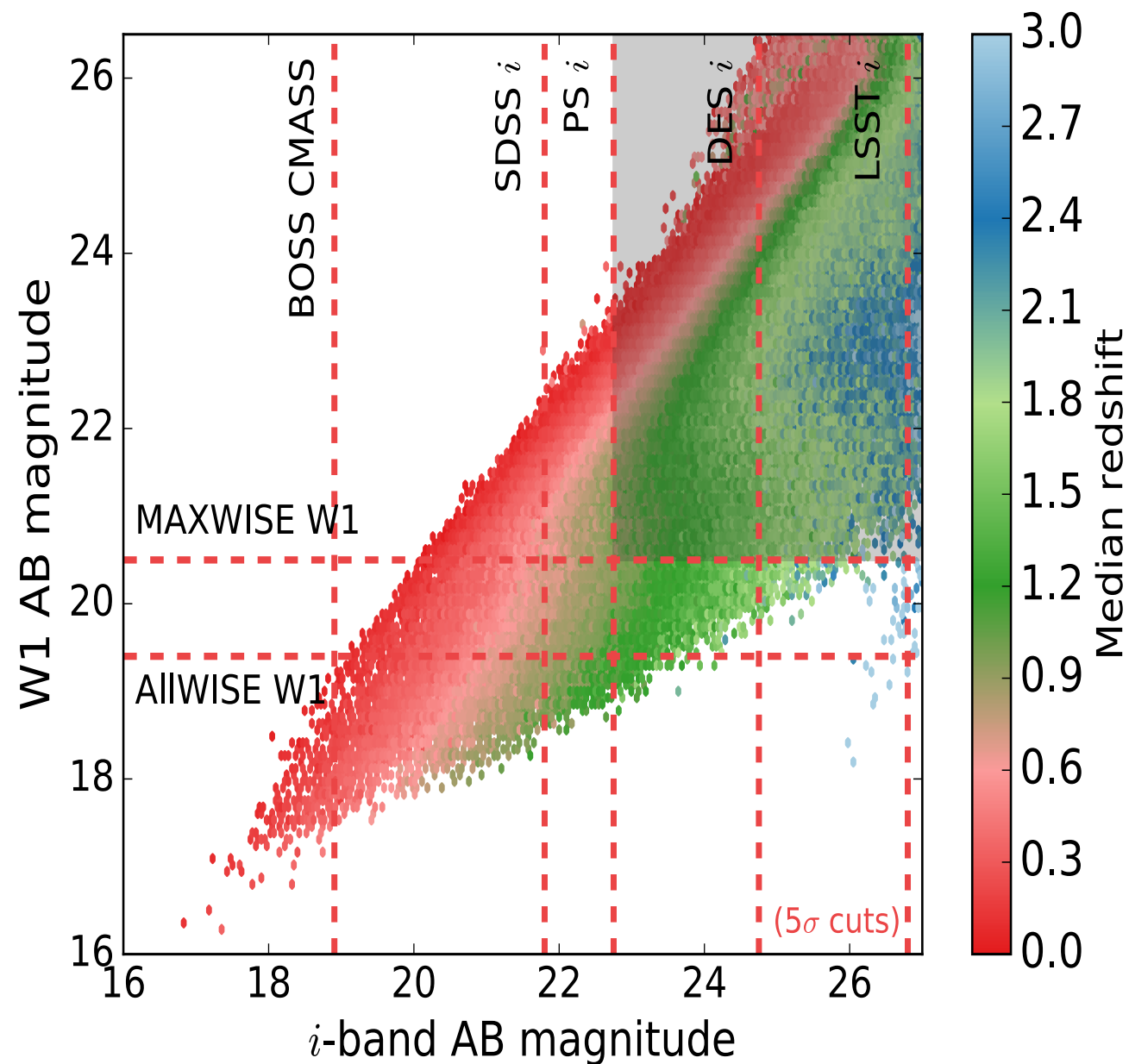
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 - ➔ Ideal for multi-tracer studies (McDonald & Seljak 09).

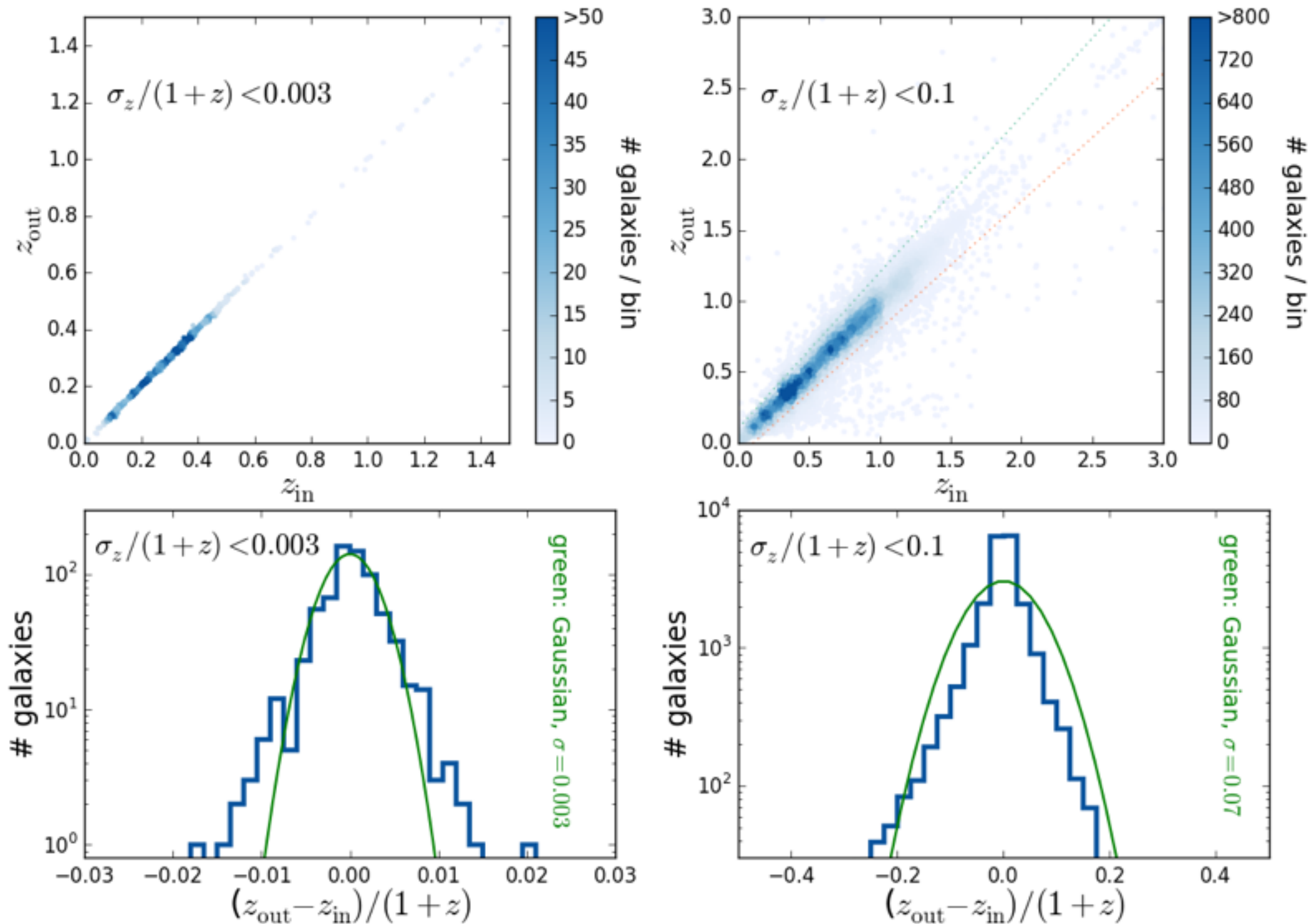
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- The power of low-resolution spectroscopy has been demonstrated with PRIMUS (Cool++14), COSMOS (Ilbert++09), NMBS (van Dokkum++09).

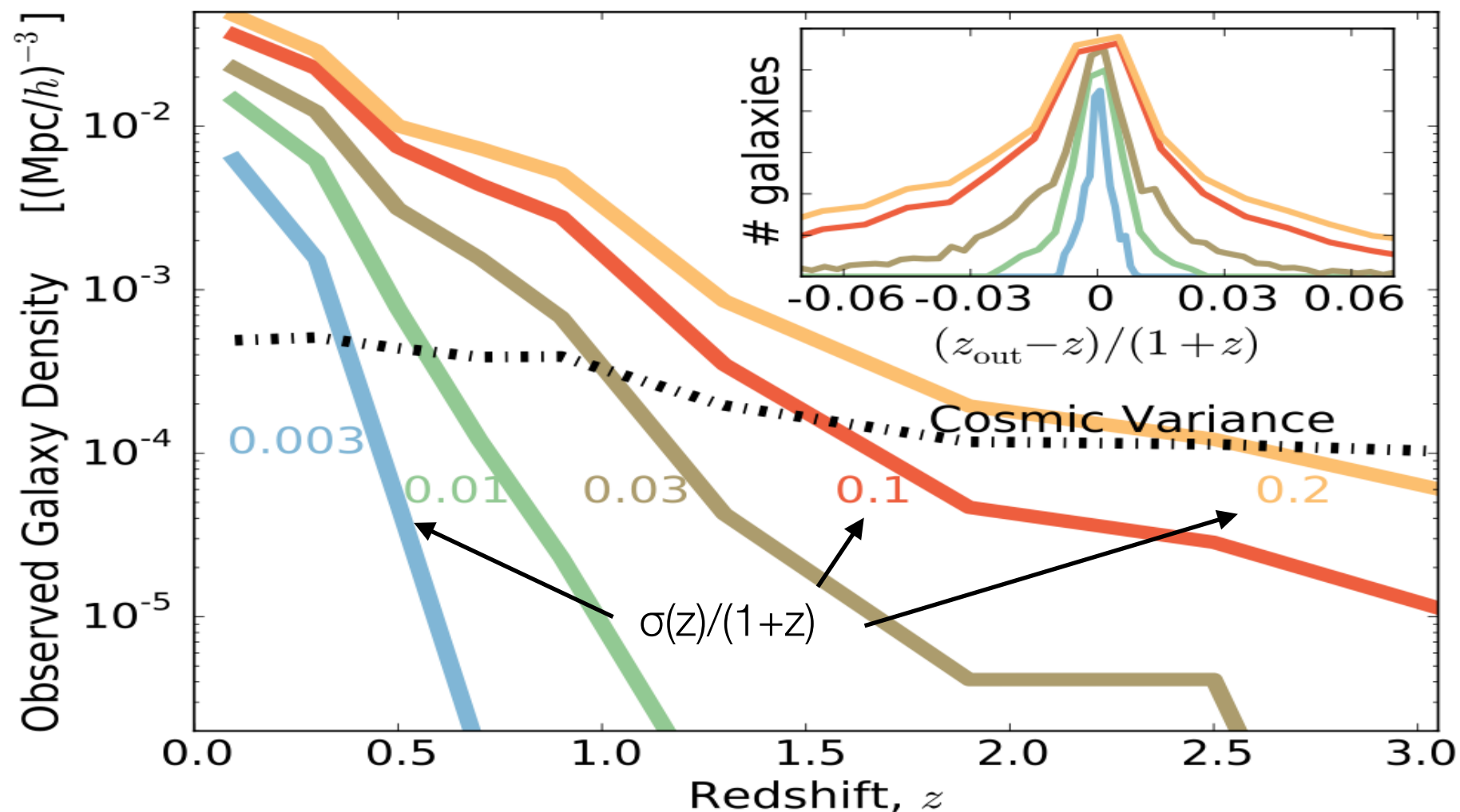
SPHEREx Simulation Pipeline



Redshift Measurement Errors



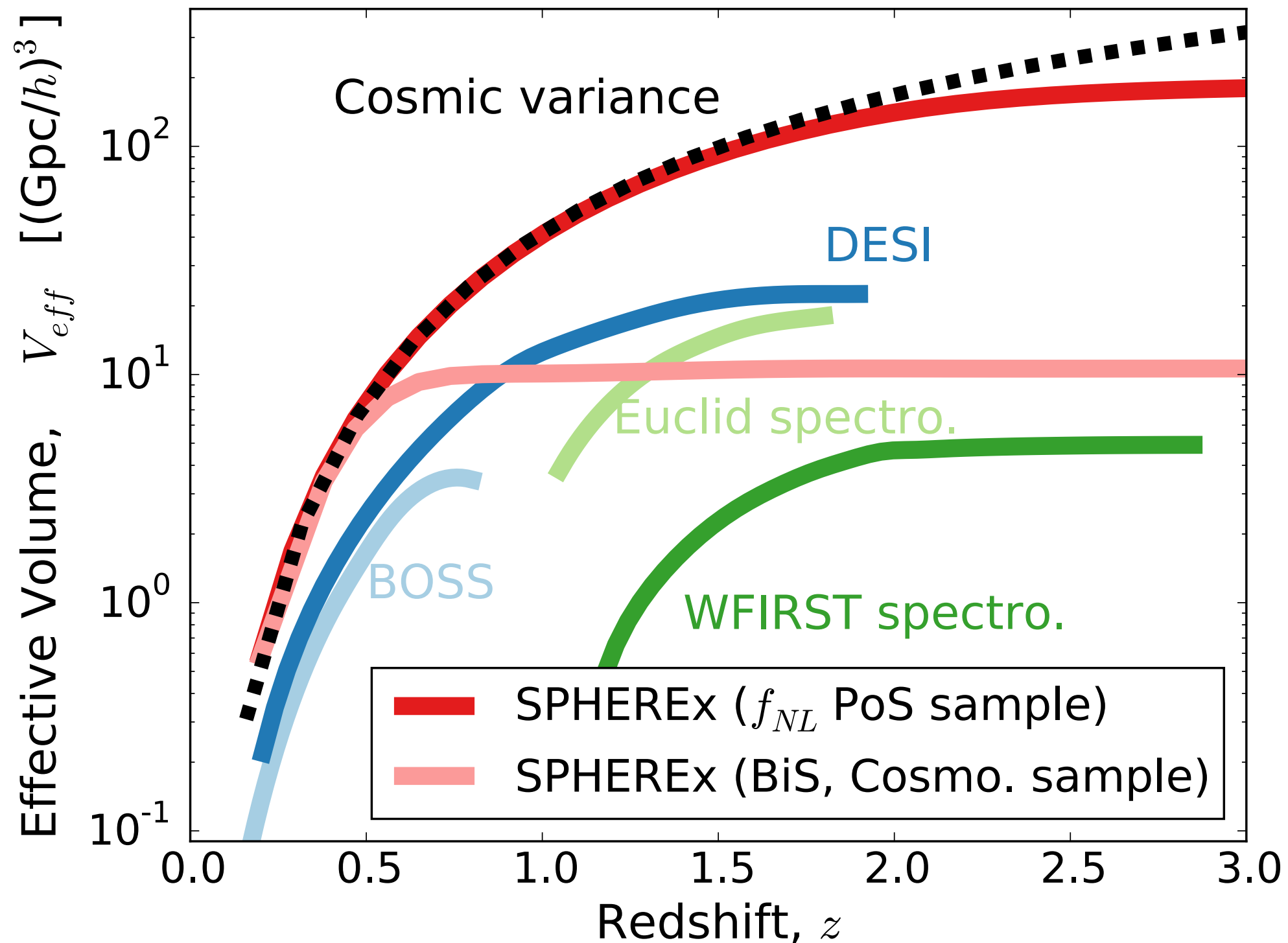
SPHEREx All-Sky Galaxy Density



- Full source extraction and redshift measurement pipeline (Capak & Masters).
- Detect 1.4 billions sources:
 - ➔ 301M of which with 10% z accuracy, 120M with 3% and 9.8M 0.3%.
- Spectra of all types of galaxies, i.e., not only emission line galaxies:
 - ➔ Ideally suited for multi-tracer studies.
- The high $\sigma(z)$ sample drives the power-spectrum f_{NL} constraints while the lower $\sigma(z)$ sample drive the bispectrum and other cosmological parameter constraints.

SPHEREx Probes a Large Effective Volume

$$V_{eff} = V_{survey} \left(\frac{P_{gal}}{P_{gal} + \frac{1}{n_{gal}}} \right)^2$$



SPHEREx and Other Surveys

- SPHEREx maps the full sky:
 - ➔ SPHEREx overlaps with your survey!
- SPHEREx has strong scientific synergies with other ground or space based surveys:
 - ➔ SPHEREx maps the low redshift universe whereas Euclid and WFIRST spectroscopic surveys target $z > 1$.
 - ➔ E.g., substantially increase ($\sim 50\%$) the SNR for galaxy-galaxy lensing if using in conjunction with deep imagers such as LSST, Euclid and WFIRST.
 - ➔ By mapping exquisitely the low- z universe, SPHEREx will help mitigate the intrinsic alignment systematic for WL (e.g., Krause++15).
 - ➔ SPHEREx will substantially help with photometric redshift errors:
 - ▶ Direct redshift measurements for bright enough sources.
 - ▶ Help reduce catastrophic failures.
 - ▶ Ideal for clustering redshift analysis (e.g., Newman++08, Ménard++13)
 - ▶ Stacking analysis might be very powerful for faint sources (study in progress w/ N. Padmanabhan, M. White et al.).
 - ➔ SPHEREx will help measuring cluster redshift over the full sky (study in progress).

Why Studying Primordial non-Gaussianity Further?

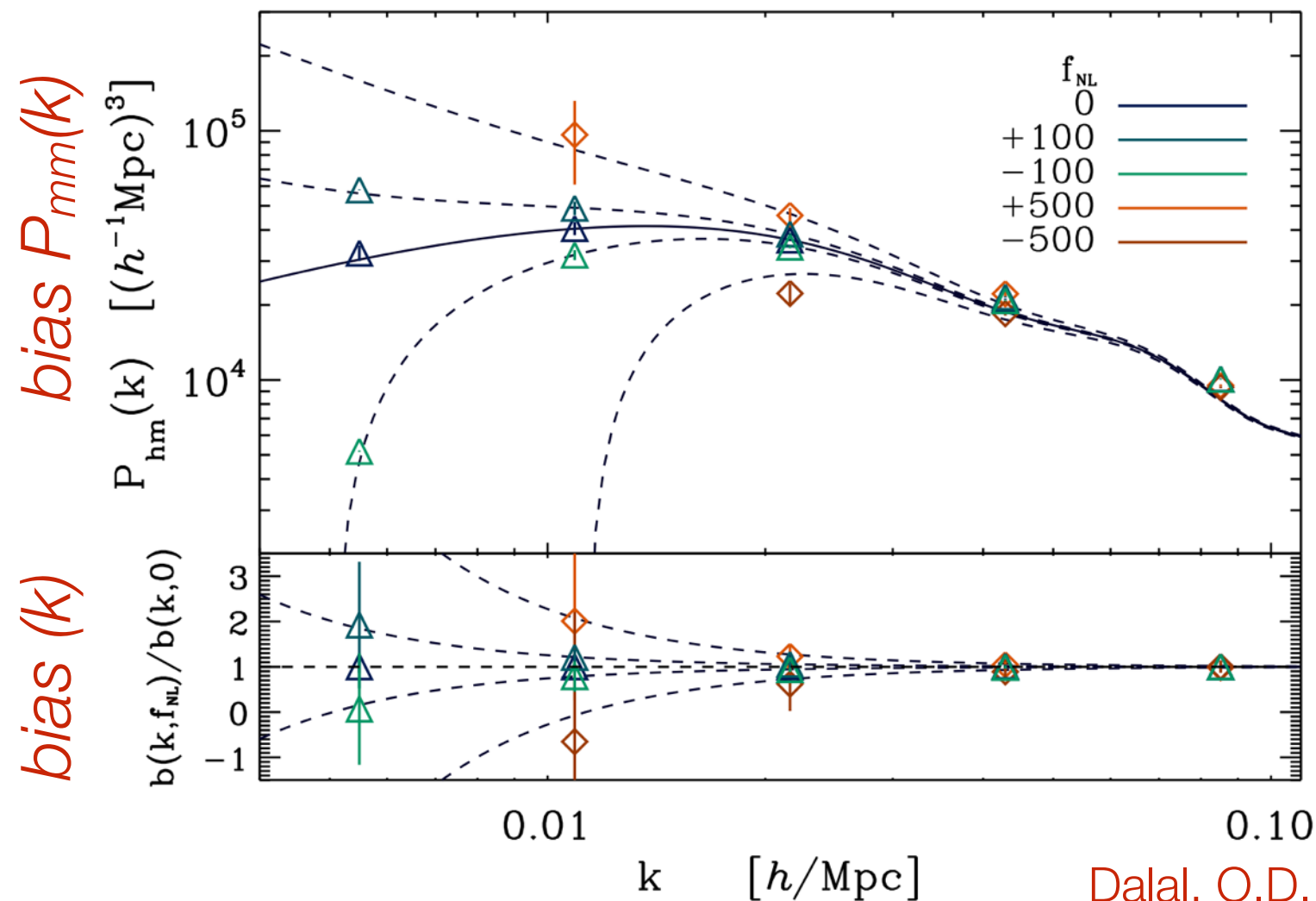
	$f_{\text{NL}}^{\text{loc}} \lesssim 1$	$f_{\text{NL}}^{\text{loc}} \gtrsim 1$
$f_{\text{NL}}^{\text{eq, orth}} \lesssim 1$	Single-field slow-roll	Multi-field
$f_{\text{NL}}^{\text{eq, orth}} \gtrsim 1$	Single-field non-slow-roll	Multi-field

- Well-defined theory targets exist.
- Planck tells us $f_{\text{NL}} \approx 5$ (68% C.L.).
- The polarized CMB cosmic variance limit is about ≈ 3 (68% C.L.)
 - ➔ Large-scale structure (3D mapping) measurements are needed.
 - ➔ $\sim 10^6$ independent modes in Planck, possibly 10^8 in future LSS surveys

*Testing Inflation with Large Scale Structure: Connecting Hopes with Reality
(conveners: O.D., D. Green, Alvarez et al., [arXiv:1412.4671](https://arxiv.org/abs/1412.4671))*

Primordial Non-Gaussianity affects Galaxy Clustering

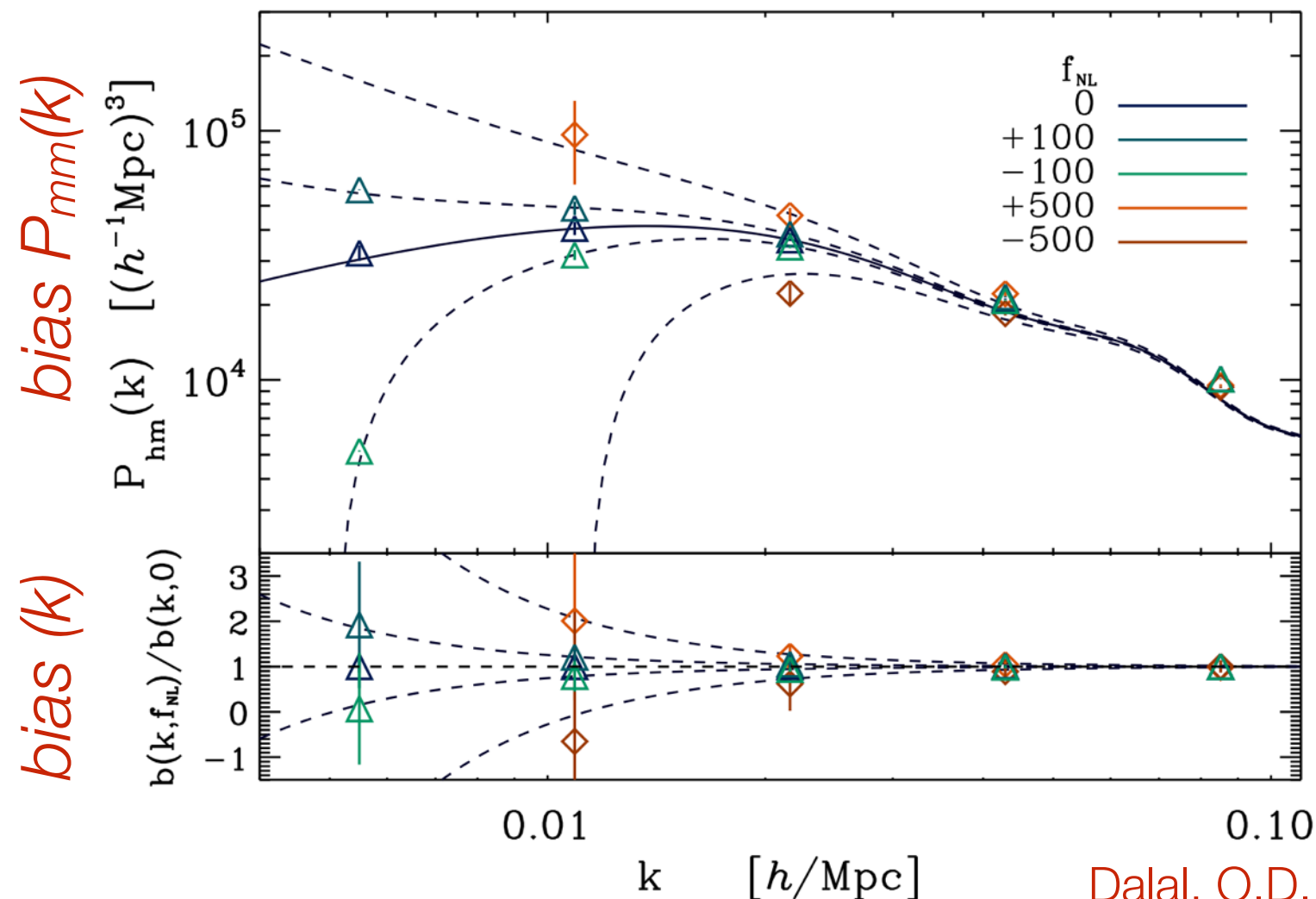
$$\delta_{\text{galaxies}}(k) = \text{bias} \delta_{\text{dark matter}}(k)$$



Dalal, O.D., Huterer, Shirokov 07

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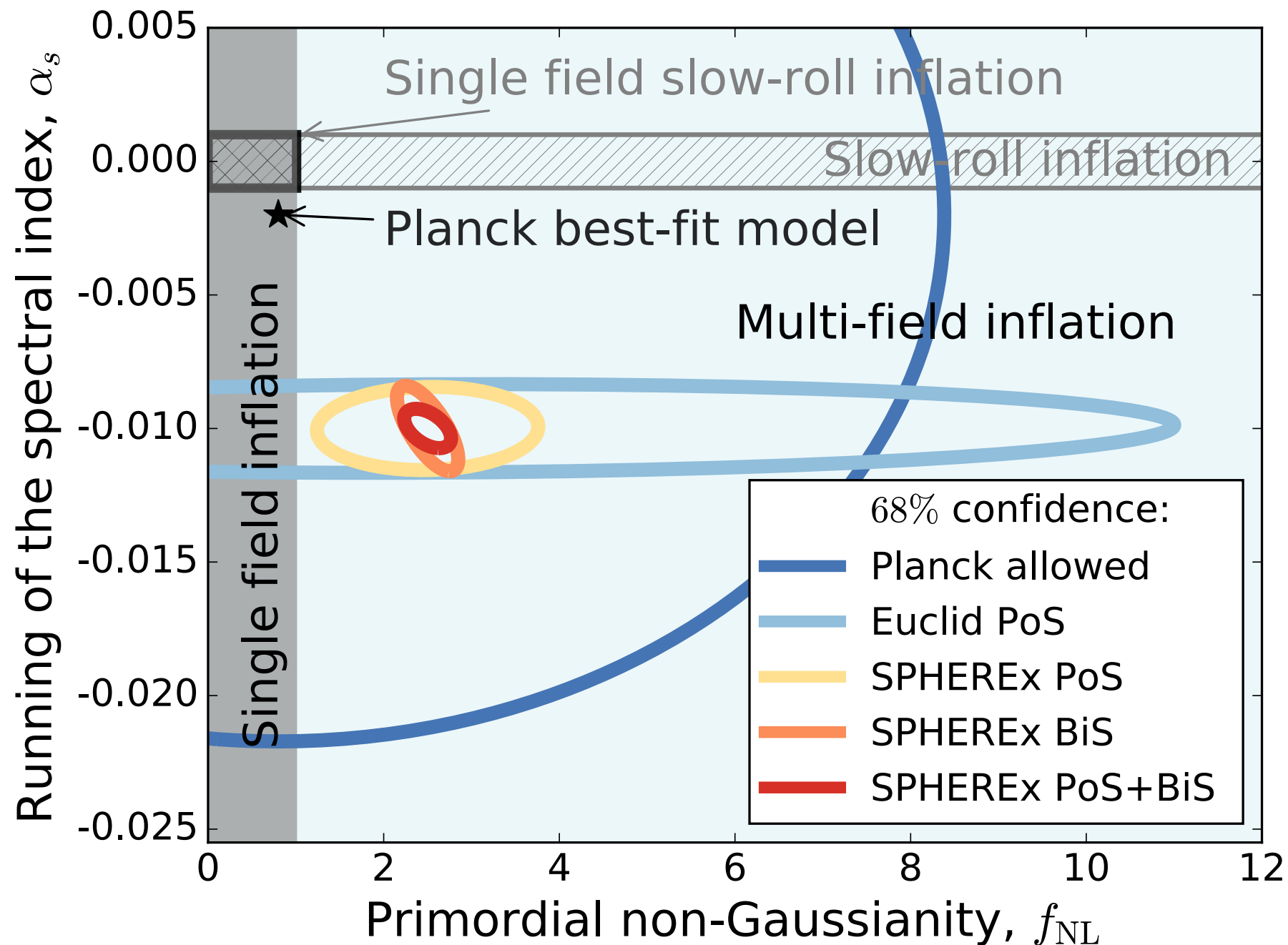


Dalal, O.D., Huterer, Shirokov 07

- The effect of primordial non-Gaussianity on galaxy clustering is most important on large scales
 ➔ Full sky survey, low spectral resolution sample (de Putter & OD, 14).
- E.g., SDSS QSOs : $-49 < f_{\text{NL}}^{\text{loc}} < 31$ (95% C.L., Leistedt & Peiris 13)

SPHEREx as a Probe of non-Gaussianity

$\sigma(f_{\text{NL}}^{\text{loc}}) \sim 0.8$ (3-D Power-spectrum)
 $\sigma(f_{\text{NL}}^{\text{loc}}) \sim 0.2$ (3-D Bispectrum)



O.D., Bock et al. 2014
Alvarez et al. 2014

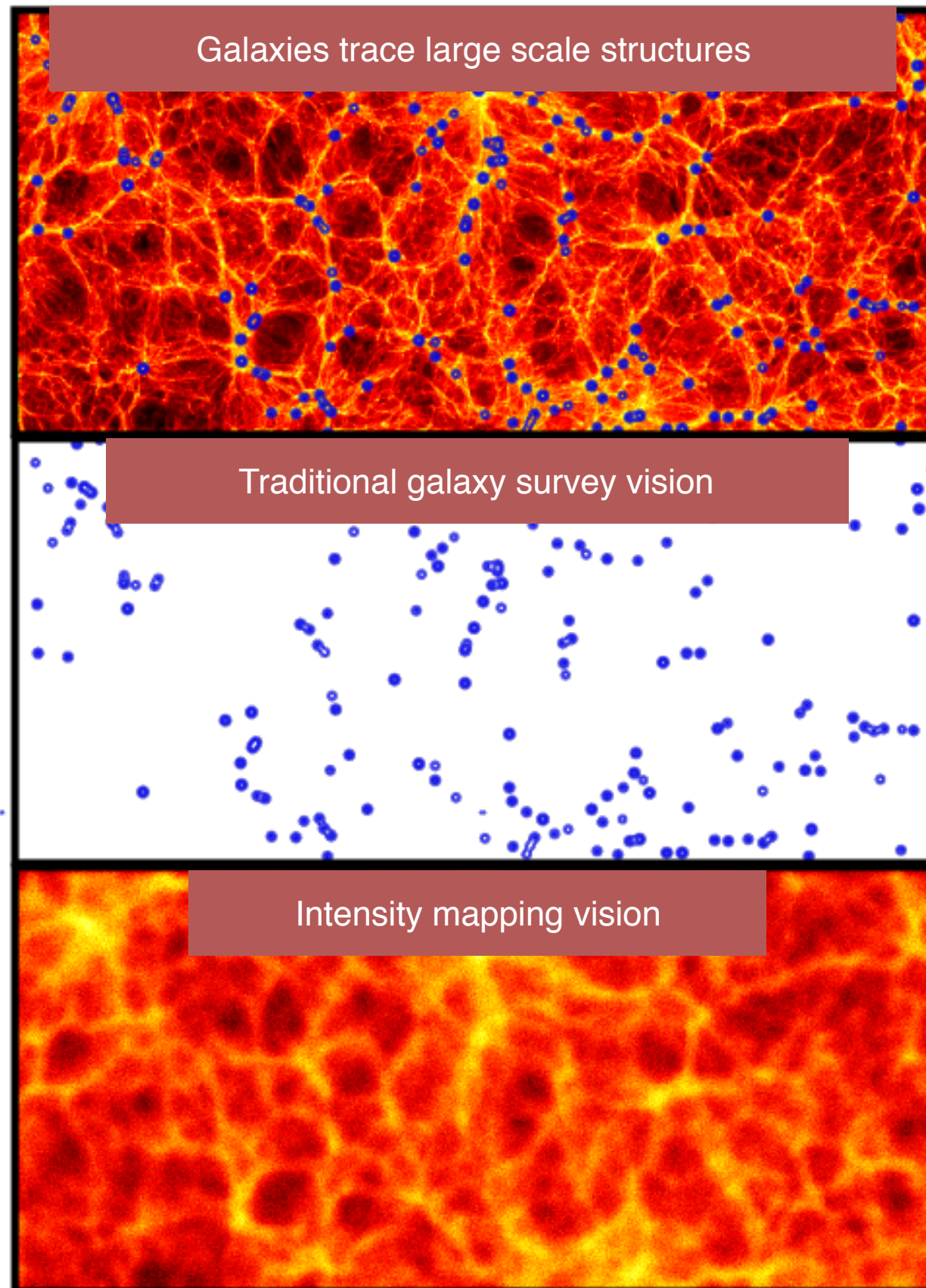
SPHEREx Cosmological Parameters Constraints

1 σ errors	PS	Bispec	PS + Bispec	EUCLID (GC)	Current
$f_{\text{NL}}^{\text{loc}}$	0.87	0.23	0.20	5.59	5.8
Tilt n_s ($\times 10^{-3}$)	2.7	2.3	2.2	2.6	5.4
Running α_s ($\times 10^{-3}$)	1.3	1.2	0.65	1.1	17
Curvature Ω_K ($\times 10^{-4}$)	9.8	NC	6.6	7.0	66
Dark Energy FoM = $1/\sqrt{\text{DetCov}}$	202	NC	NC	309	25

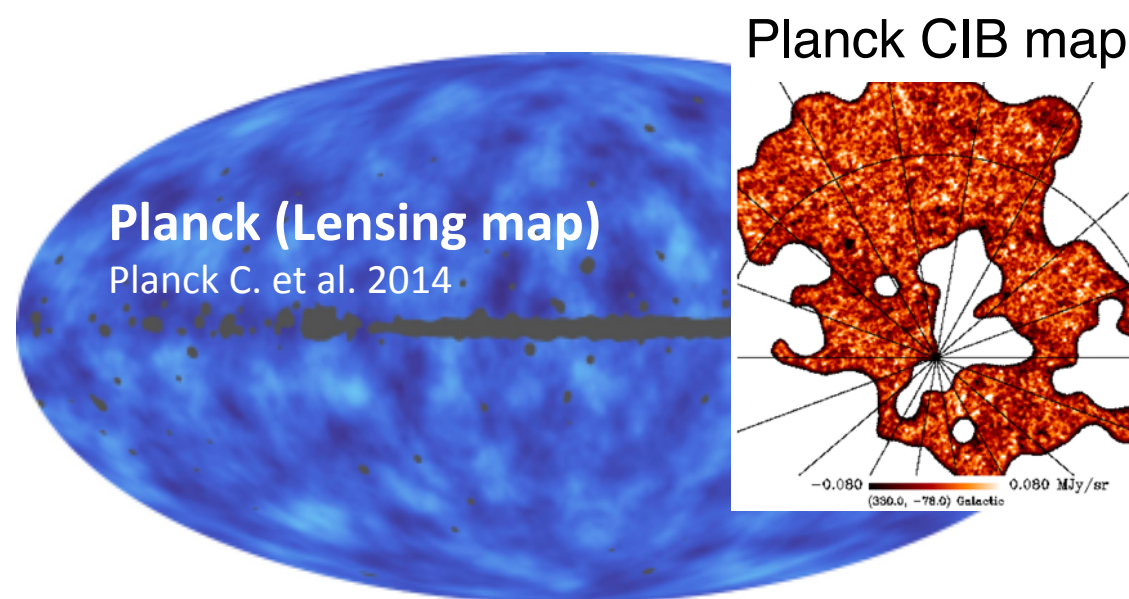
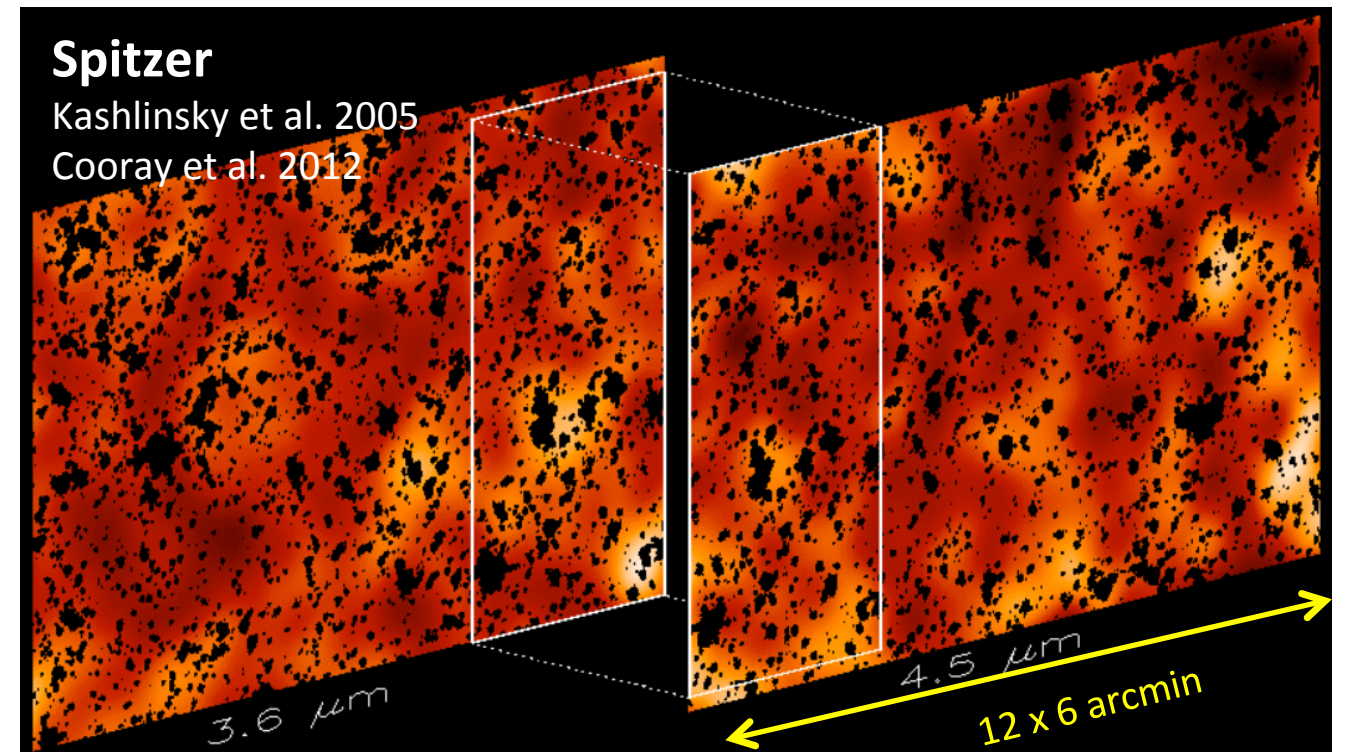
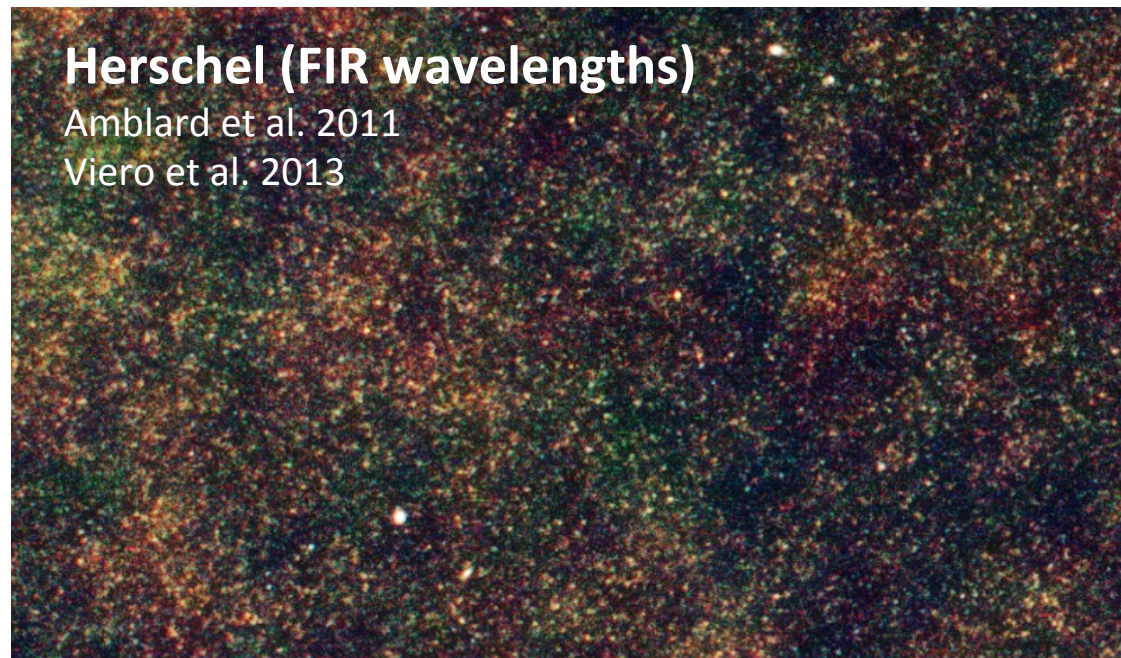
Using the power spectrum only and assuming Planck prior

Galaxy Evolution Investigation

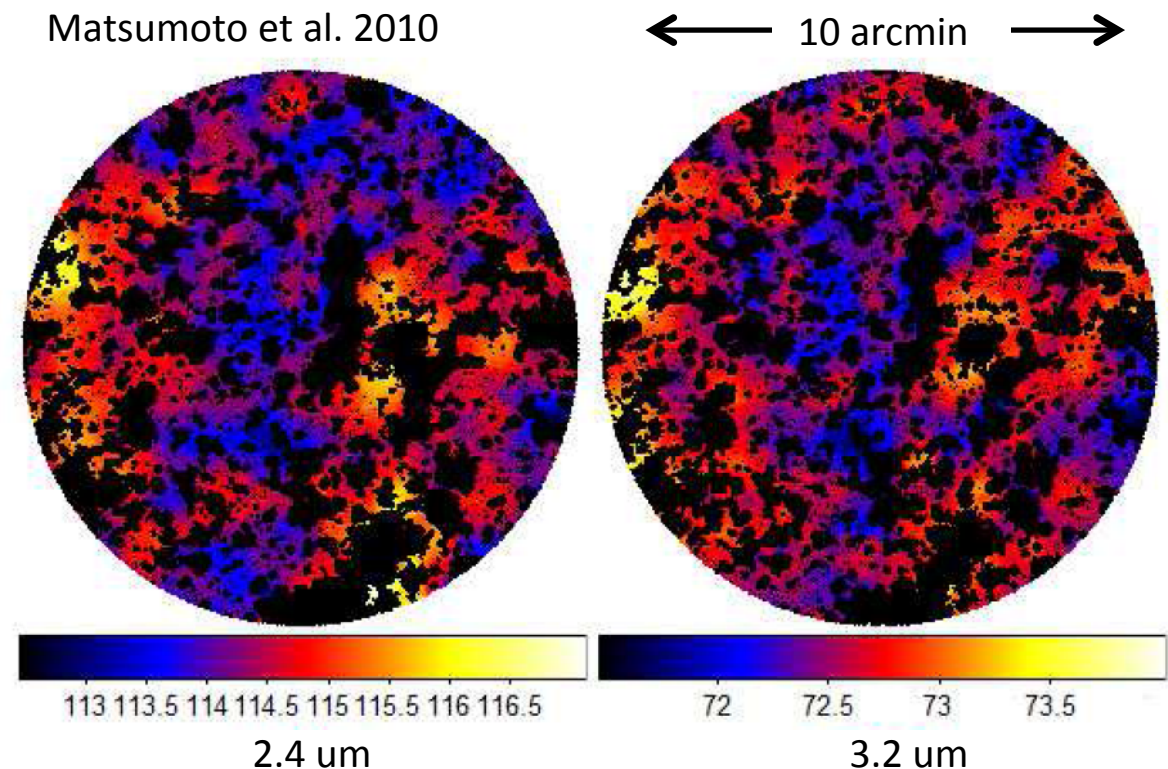
Astronomy in the Intensity Mapping Regime



Probing the EBL with Spatial Fluctuations in NIR or mm



Akari
Matsumoto et al. 2010



Successful Applications at Longer Wavelengths

Herschel EBL: Viero et al. 2013

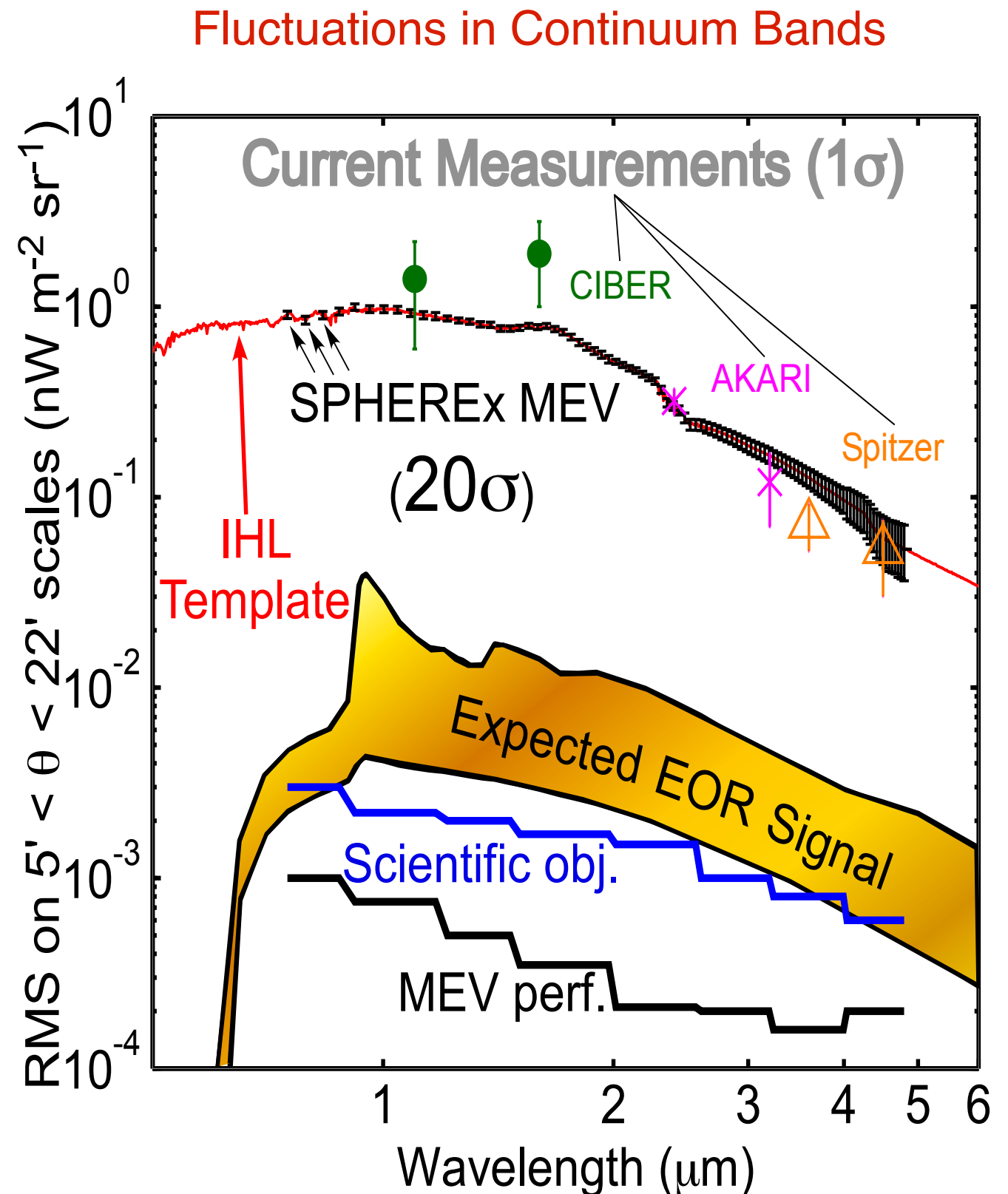
Planck EBL: Planck C. et al. 2013 XXX

Planck EBL x CMB Lensing: Planck C. et al. 2014 XVIII

Herschel EBL x CMB Lensing: Many

Probing the Epoch of Reionization with SPHEREx

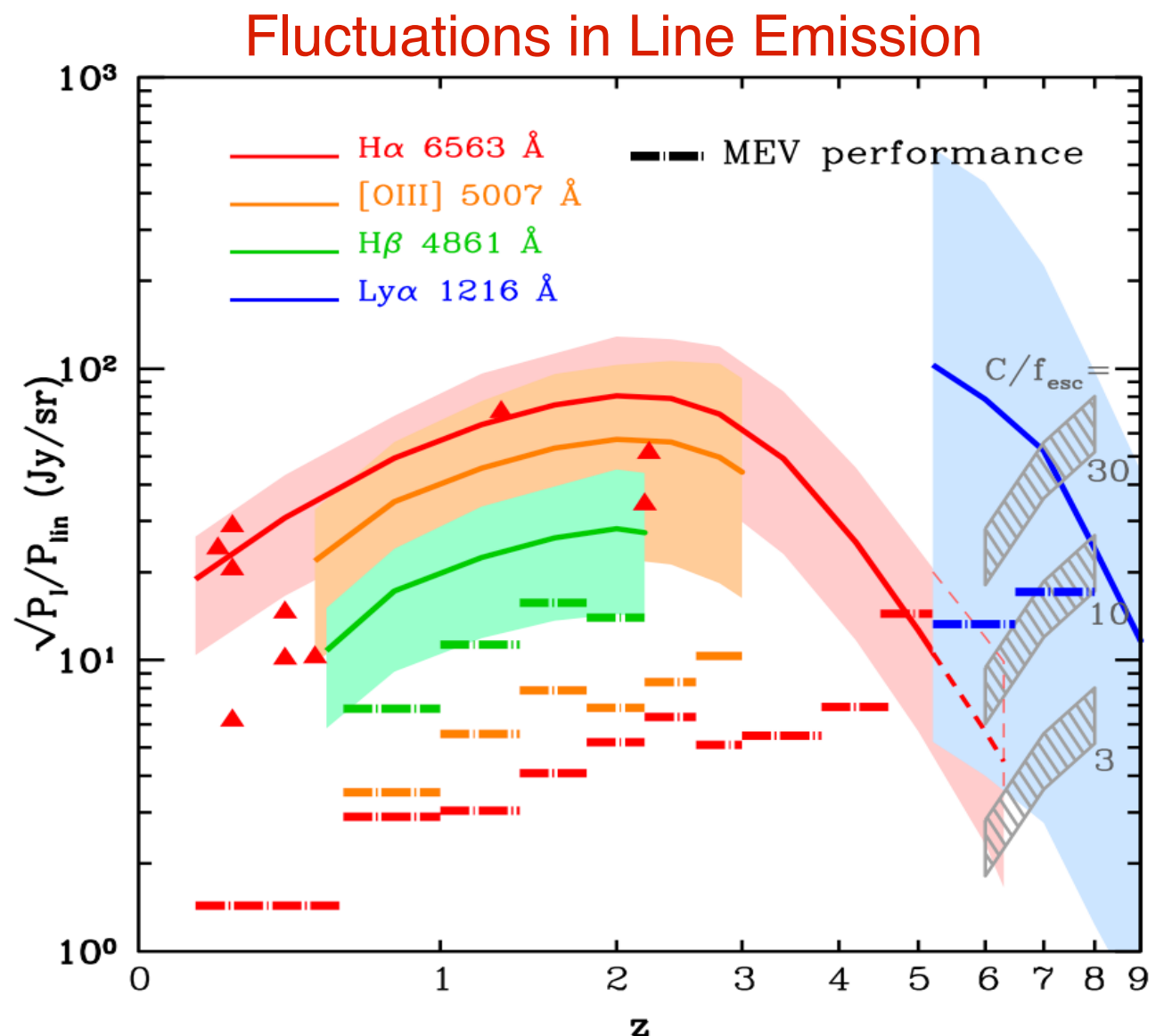
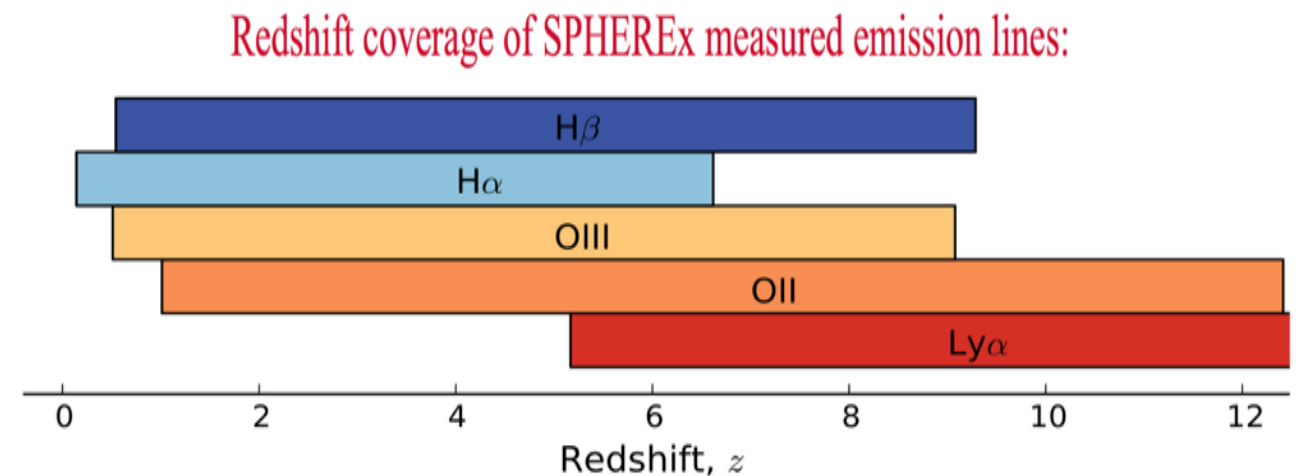
- SPHEREx orbits enable deep/frequent observations of about 200 sq. deg near the ecliptic poles (great for systematics!)
- SPHEREx wavelength coverage and resolution will enable large-scale measurement of spatial fluctuations in the Extragalactic Background Light (EBL).
- In particular, SPHEREx will monitor/explain the Intra-Halo Light and its evolution (CIBER, Zemcov++14).
- SPHEREx has the raw sensitivity to probe the expected EOR signal (but separation with low z signal will be challenging).
- The sensitivity in this region will enable deep intensity mapping regimes using multiple lines at all redshift, and maybe Ly α at high redshift (see Croft++15)



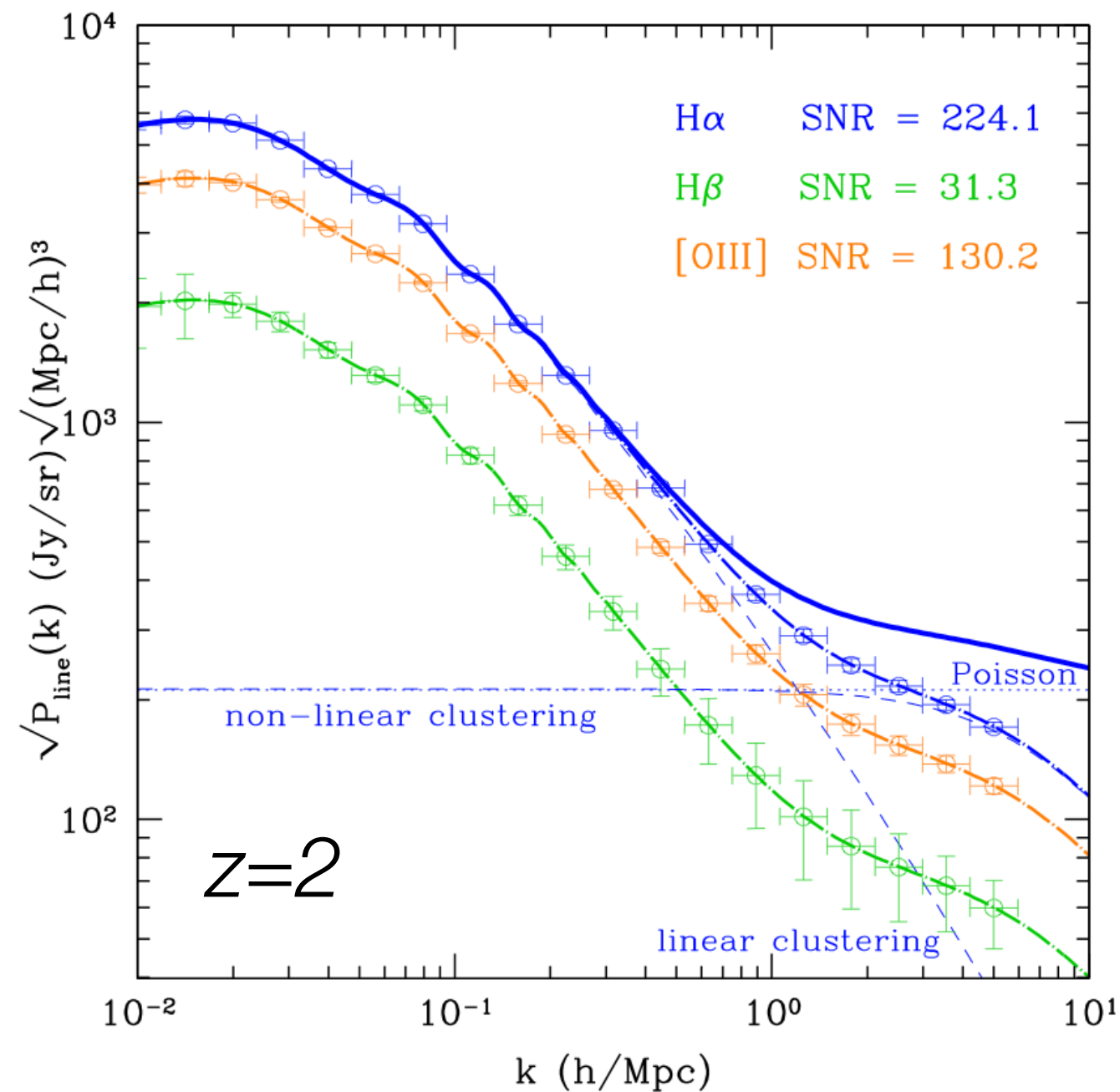
Intensity Mapping 3D Clustering with SPHEREx

- SPHEREx (SEO) will measure with high SNR the *line luminosity weighted bias* at multiple redshifts with multiple emission lines.
- This bias is directly proportional to the total light production at a given time and thus proportional to the SFR.
- SPHEREx will map SFR throughout cosmic times, when it increases, peaks and declines.
- SPHEREx *might* have sensitivity to detect Ly α from EOR.

Clustering amplitude (bias)

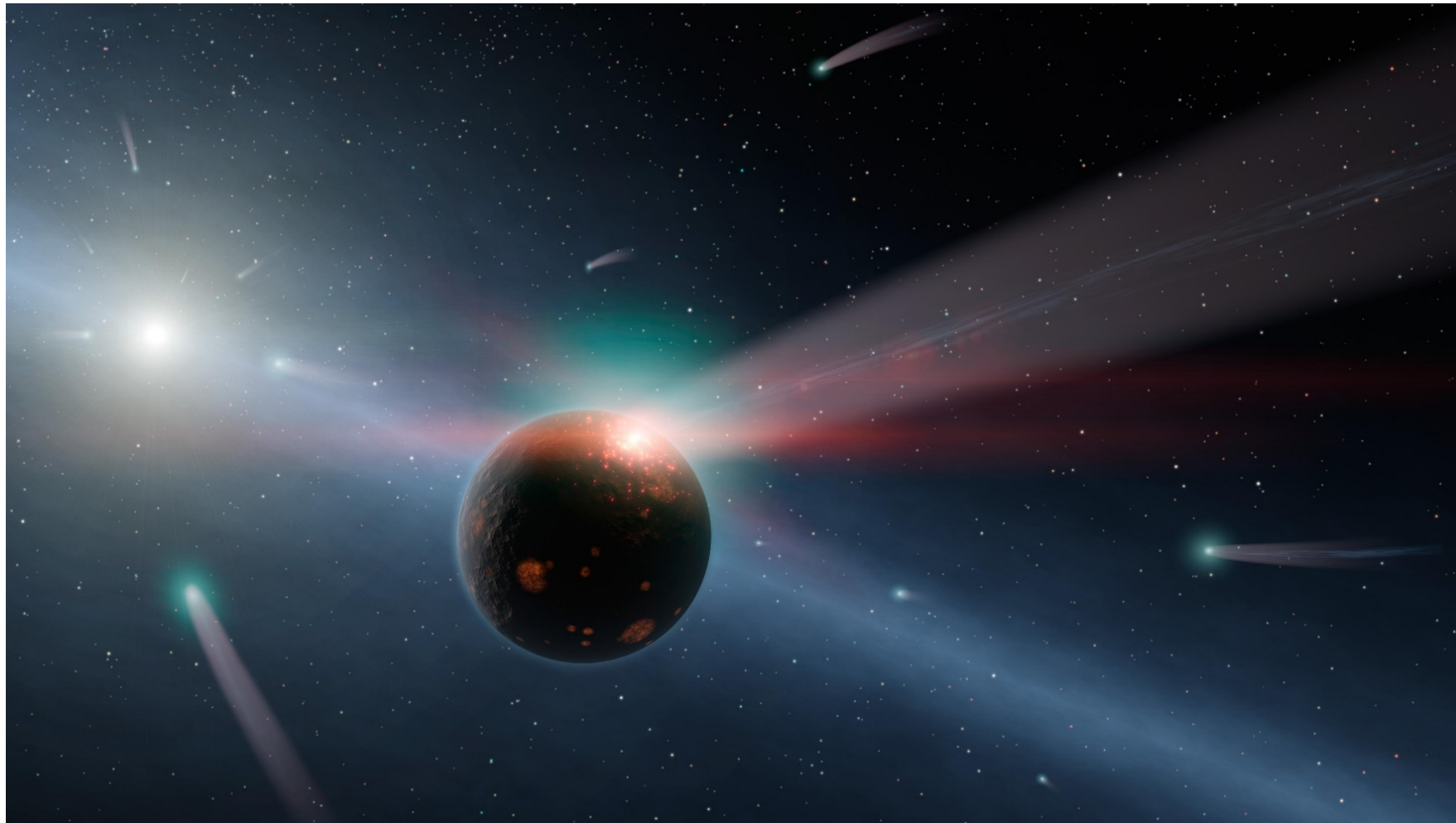


Intensity Mapping 3D Clustering with SPHEREx at $z=2$



Ice Investigation

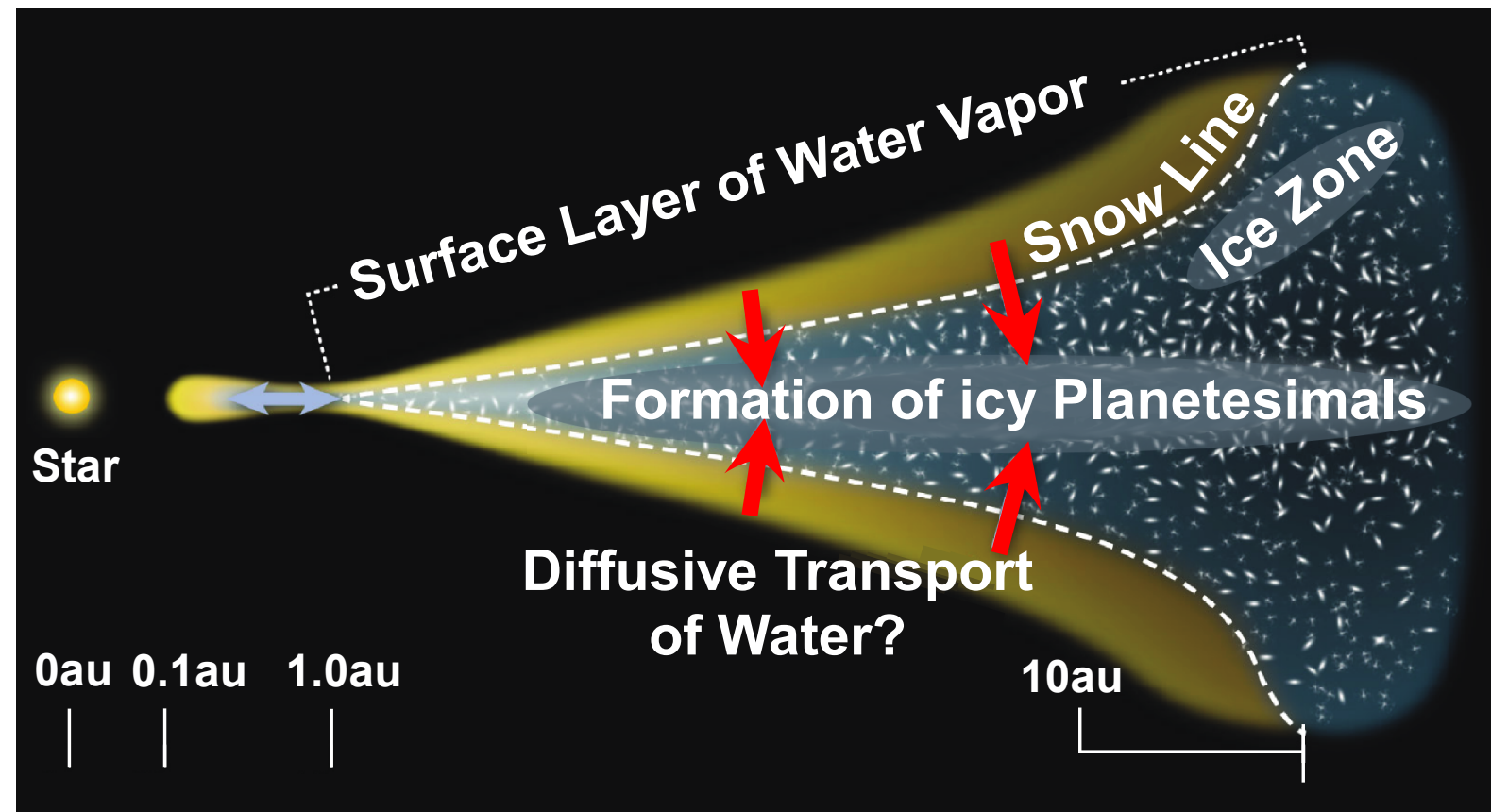
How Did the Earth's Water Originate?



- Sourced by interstellar ices, rich in biogenic molecules: H_2O , CO , CO_2 , CH_3OH ...
- Current debate:
 - ➔ Did water come from the Oort cloud, Kuiper belt or closer in?
 - ➔ Did water arrive from the late bombardment (~500 MY) or before?
 - ▶ D/H of earth's oceans is 10x solar.
 - ▶ D/H varies between comet families, KBOs and asteroids.

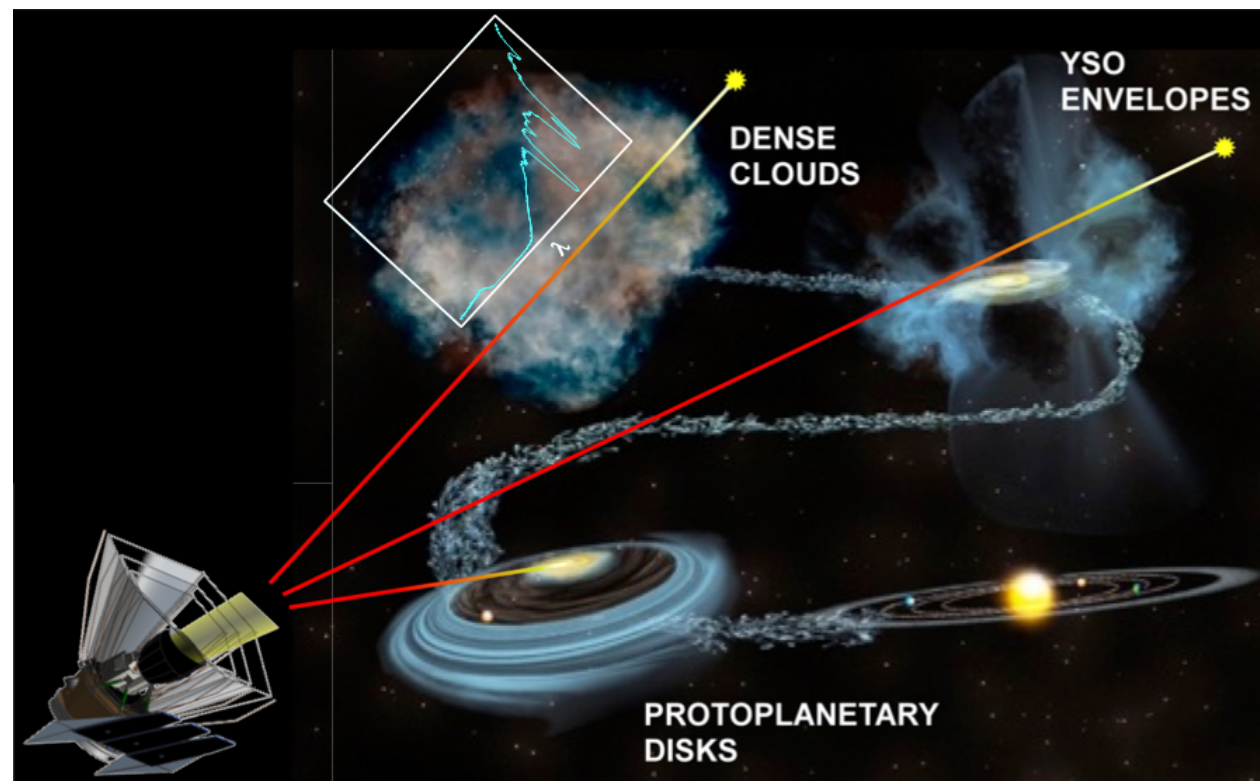
SPHEREx Galactic Ice Investigation: Why?

- Gas and dust within dense molecular clouds are the reservoirs from which stars and planets assemble:
 - ➔ Within molecular clouds, H_2O ice abundance is $10^2 - 10^3 \times$ greater than H_2O gas.
- In young protoplanetary disks, both models and the limited data presently available suggest that substantial amounts of water and, perhaps other biogenic molecules, exist primarily in ice toward the disk mid-plane and beyond the snow line.
 - ➔ Herschel observations of the TW Hydrae disk imply the presence of 1000s of Earth oceans in ice (Hogerheijde et al. 2011)



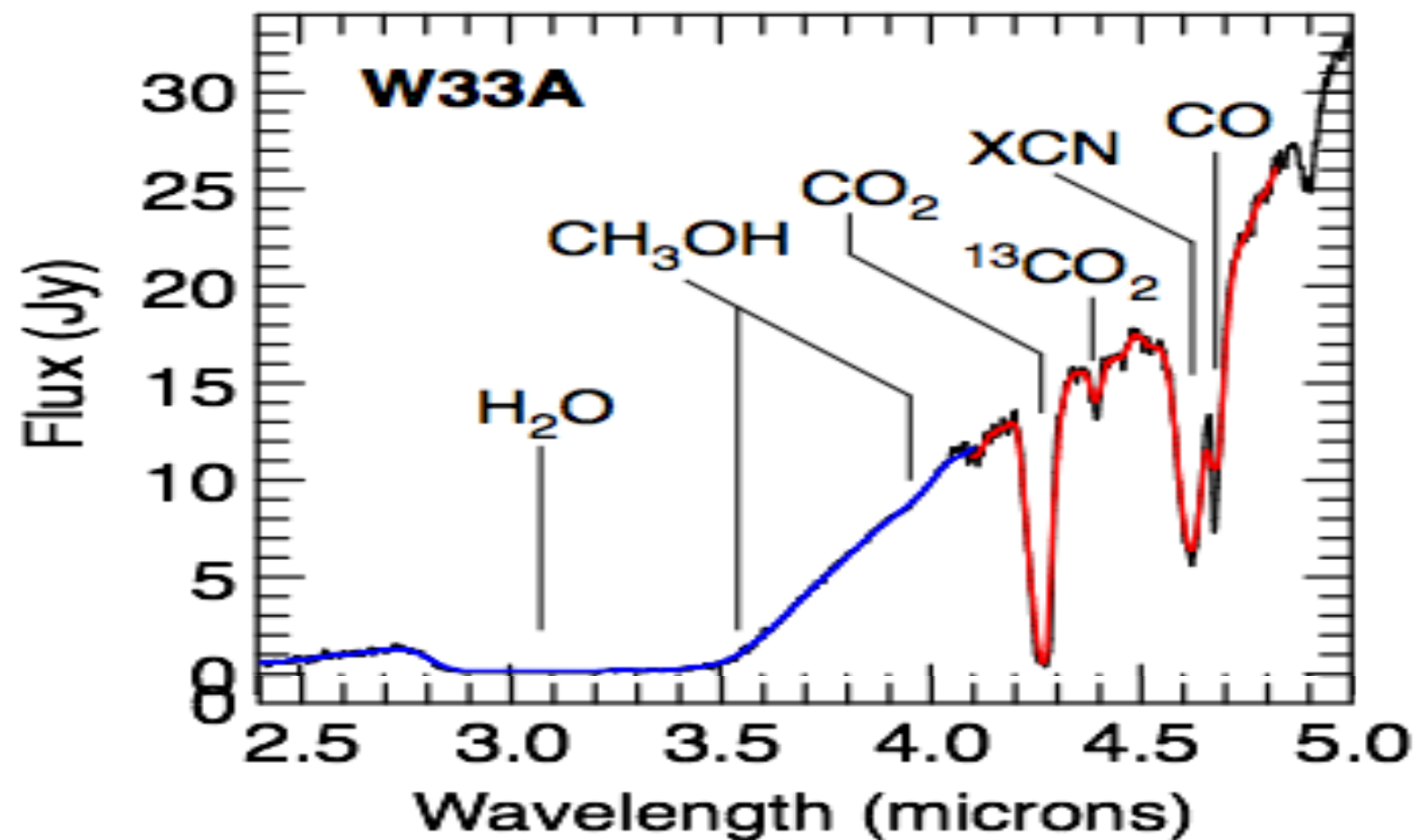
SPHEREx Galactic Ice Investigation: How?

- SPHEREx will use point sources as background targets for absorption spectroscopy:
 - ➔ WISE has catalogued $>10^6$ (non-confused) galactic sources at $3.4\ \mu\text{m}$ and $4.6\ \mu\text{m}$ with evidence for extinction due to intervening gas and dust.
 - ➔ SPHEREx will measure their spectra with a $\text{SNR} > 100$ per $\Delta\lambda$.



- The SPHEREx ice catalog will:
 - ➔ Contain molecular clouds, YSOs, and 1000s of protoplanetary disks.
 - ➔ Determine the role of environment (T , n , radiation field, cosmic rays) in forming ices.
 - ➔ Determine if ices in disks come from the parent cloud or are reformed.
 - ➔ Measure the abundance of water and biogenic ices in disks that is available to new plants.

SPHEREx Galactic Ice Investigation: How?



- SPHEREx will be a game changer in our efforts to resolve long-standing questions about the amount and evolution of key biogenic molecules (H₂O, CO, CO₂, and CH₃OH) through all phases of star and planet formation by:
 - ➔ Increasing the number of ice absorption spectra from 20 to >> 20,000.
 - ➔ Observing in a spectral region rich in ice features of several key species: H₂O, CO and CO₂.
 - ➔ Plus chemically important minor constituents NH₃, CH₃OH, X-CN, and ¹³CO.
 - ➔ Spectral resolution high enough to isolate absorption due to each species; pixels small enough to avoid confusion; high SNR.

Conclusions: Ready for Phase A!

- SPHEREx has been proposed in Dec.14 as a SMEX mission and selected for Phase-A study in August 15.
- SPHEREx will create the first all sky near-infrared spectroscopic survey:
 - ➔ SPHEREx will create a dataset of lasting legacy.
- SPHEREx offers a simple and very robust design and modus operandi:
 - ➔ It naturally enables a high control of systematics thanks to multiple built-in redundancy.
- SPHEREx key cosmology goals are complementary to CMB based constraints:
 - ➔ It allows to probe non-Gaussianity better than any planned experiment (x5 better than Planck/Euclid using the power spectrum and x10 using the bispectrum).
 - ➔ It is sensitive enough to probe regions of well defined theoretical interests.
- SPHEREx is complementary to and has strong synergies with Euclid and WFIRST:
 - ➔ It probes the $z < 1$ Universe while Euclid and WFIRST galaxy clustering studies focus on the higher z Universe.
 - ➔ SPHEREx will facilitate the control of systematics for Euclid and WFIRST (e.g., photo- z , intrinsic alignment,...) while enabling new scientific opportunities (e.g., exquisite galaxy-galaxy lensing, magnification, ...).
- SPHEREx will also enable other original and powerful studies:
 - ➔ The extra-galactic background light from $z=0$ till the reionization era.
 - ➔ The origin of water and biogenic ices in young stellar objects and protoplanetary systems.
- Community support is important!
 - ➔ If you want SPHEREx to happen, please mention it in your papers or talks.

<http://spherex.caltech.edu>

FIN
